Probabilistic Accident Consequence Uncertainty Analysis

Dispersion and Deposition Uncertainty Assessment

Volume 1 Main Report

A Joint Report Prepared by U.S. Nuclear Regulatory Commission and Commission of European Communities

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Abstract

The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was completed in 1990. These codes estimate the risks presented by nuclear installations based on postulated frequencies and magnitudes of potential accidents. In 1991, the US Nuclear Regulatory Commission (NRC) and the Commission of the European Communities (CEC) began a joint uncertainty analysis of the two codes. The ultimate objective of the joint effort was to develop credible and traceable uncertainty distributions for the input variables of the codes. As a first step, a feasibility study was conducted to determine the efficacy of evaluating a limited phenomenological area of consequence calculations (atmospheric dispersion and deposition parameters) and to determine whether the technology exists to develop credible uncertainty distributions on the input variables for the codes. Expert elicitation was identified as the best technology available for developing a library of uncertainty distributions for the selected consequence parameters.

The study was formulated jointly and was limited to the current code models and to physical quantities that could be measured in experiments. The elicitation procedure was devised from previous US and EC studies with refinements based on recent experience. Elicitation questions were developed, tested, and clarified. Sixteen internationally recognized experts from nine countries were selected using a common set of selection criteria. Probability training exercises were conducted to establish ground rules and set the initial boundary conditions. Experts developed their distributions independently. Results were processed with an equal weighting aggregation method, and the aggregated distributions were processed into code input variables. To validate the distributions generated for the wet deposition input variables, samples were taken from these distributions and propagated through the wet deposition code model. Resulting distributions closely replicated the aggregated elicited wet deposition distributions. To validate the distributions generated for the dispersion code input variables, samples were taken from the distributions and propagated through the Gaussian plume model (GPM) implemented in the MACCS and COSYMA codes. Resulting distributions were found to well replicate aggregated elicited dispersion distributions consistent with the GPM assumptions.

Valuable information was obtained from the elicitation exercise. Project teams from the NRC and CEC cooperated successfully to develop and implement a unified process for the elaboration of uncertainty distributions on consequence code input parameters. Formal expert judgment elicitation proved valuable for synthesizing the best available information. Distributions on measurable atmospheric dispersion and deposition parameters were successfully elicited from experts involved in the many phenomenological areas of consequence analysis.

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Preface

This volume is the first of a three-volume document that summarizes a joint project conducted by the US Nuclear Regulatory Commission and the Commission of European Communities to assess uncertainties in the MACCS and COSYMA probabilistic accident consequence codes. These codes were developed primarily for making estimates of the risks presented by nuclear reactors based on postulated frequencies and magnitudes of potential accidents. This three-volume document reports on an ongoing project intended to assess uncertainty in the MACCS and COSYMA offsite radiological consequence calculations for hypothetical nuclear power plant accidents. A panel of 16 experts was formed to compile credible and traceable uncertainty distributions for the dispersion and deposition code input variables that affect offsite radiological consequence calculations. The expert judgment elicitation procedure and its outcomes are described in these volumes.

Volume I contains background information and a complete description of the joint consequence uncertainty study. Volume II contains two appendices that include (1) the rationales for the dispersion and deposition data provided by the 16 experts who participated in the elicitation process, (2) the tabulated elicited information, and (3) short biographies of the 16 experts. Volume III contains six appendices that describe in greater detail the specific methodologies used by the atmospheric dispersion and deposition panels.

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List of Acronyms

ACC	accident consequence codes
ARAC	Atmospheric Release Advisory Capability
CDF	cumulative distribution function
CEC	Commission of the European Communities
COSYMA	Code System from MARIA
EC	European Communities
GPM	Gaussian plume model
GRS	German Institute for Reactor Safety
KfK	German Nuclear Research Center Karlsruhe
LHS	Latin Hypercube Sampling
MACCS	MELCOR Accident Consequence Code System
MARIA	Methods for Assessing the Radiological Impact of Accidents
NRC	Nuclear Regulatory Commission
NRPB	National Radiological Protection Board
PDF	probability density function
PRA	probabilistic risk analysis
SNL	Sandia National Laboratories
SUSA	software system for uncertainty and sensitivity analysis

Executive Summary

Introduction

The US Nuclear Regulatory Commission (NRC) and the Commission of the European Communities (CEC) have co-sponsored an uncertainty analysis of their respective probabilistic consequence codes, MACCS and COSYMA. Although uncertainty analyses have been performed for the predecessors of MACCS and COSYMA, the distributions for the input variables were largely developed by the code developers rather than the experts involved in the numerous phenomenological areas of a consequence analysis. In addition, both organizations were aware of the key role of uncertainty in decisions involving the prioritization of activities and research, and they were interested in initiating a comprehensive assessment of the uncertainty in consequence calculations used for risk assessments and regulatory purposes. Therefore, the ultimate objective of the NRC/CEC joint effort is to systematically develop credible and traceable uncertainty distributions for the respective code input variables using a formal expert judgment elicitation process. Expert judgment techniques are to be used only for the most important code input parameters in terms of contribution to the uncertainty in code predictions. Less resource intensive methods will be used for the development of uncertainty distributions for the remainder of the code input parameters. Each organization will then propagate and quantify the uncertainty in the predictions produced by their respective codes. Because of the magnitude and expense required to complete a full-scale consequence uncertainty analysis, a trial study was performed to evaluate the feasibility of such a joint study by initially limiting efforts to the dispersion and deposition code input variables. The specific goals of the trial study were as follows: (1) to develop a library of uncertainty distributions in the areas of radionuclide dispersion and deposition by using a formal expert judgment elicitation process; (2) to determine whether the technology exists for the development of credible uncertainty distributions on the input variables of MACCS and COSYMA; (3) to evaluate the ability of teams from the CEC and NRC to work together effectively. This report will focus on the methods used in and results of this trial study.

Approach

The state-of-the-art approach was formulated jointly based on two important ground rules: (1) the current code models would not be changed because both the NRC and CEC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would only be asked to assess physical quantities that could be hypothetically measured in experiments. Benefits of these ground rules are: (1) the codes have already been developed and applied in US and EC risk assessments, and (2) eliciting physical quantities avoids ambiguity in variable definitions; more importantly, the elicited physical quantities are not tied to any particular model and thus have a much wider potential application.

To ensure the quality of the elicited information, a formal expert judgment elicitation procedure, built on the process developed for and used in the NUREG-1150 study, was followed. Refinements were implemented based on the experience and knowledge gained from several formal expert judgment elicitation exercises performed in the US and EC since the NUREG-1150 study, such as the pilot dispersion and deposition uncertainty study sponsored by the CEC and waste repositories performance assessments in the US. The actual study was separated into the following phases: preparation stage, first expert meeting, preparation of the assessments and written rationale, second expert meeting, and processing the elicited results. Each of these will be summarized below.

Preparation Stage

Elicitation variables were defined based on the results of past and contemporary probabilistic consequence code sensitivity/uncertainty studies, which screened for the important code input variables in the context of their contribution to the uncertainties in the code predictions. Elicitation questions, hereafter referred to as case structure, were developed in accordance with the sophistication of the respective code models so that sufficient information would be elicited from the experts to allow valid interpolation and extrapolation of the resulting uncertainty distributions. The proposed case structure was then tested with several internal phenomenological experts and refined.

Two external expert selection committees were established in the US and the EC, respectively. The committees were charged with expert selection based on a common set of selection criteria, which included reputation in the relevant fields, number and quality of publications, familiarity with the uncertainty concepts, diversity in background, balance of viewpoints, interest in this project, and availability to undertake the task in the timescale prescribed. Two panels of internationally recognized scientists, as listed in

Table ES-1, were formed to participate in the formal elicitation process.

A brief project description containing the objective of the joint program, the definition of the elicitation variables, and the sample case structure was sent to the selected experts prior to the first expert meeting to familiarize the experts with the project.

First Expert Meeting

Presentations were delivered to the experts, which provided a review of the project description and objectives, the MACCS and COSYMA codes, and the treatment of the elicited information. In addition, a main focus of this meeting was to hold a probability training session in which the concept of uncertainty and potential pitfalls in preparing subjective assessments were delineated to the experts, followed by practicing exercises. Material for the training exercise was drawn directly from the fields of dispersion and deposition. Another important objective of the first expert meeting was to ensure that all the experts developed their respective uncertainty distributions based on the same basic ground rules and initial and boundary conditions. The full proposed case structure was presented to the experts for discussion and, when necessary, was modified in accordance with the feedback from the experts to ensure all given problem conditions were clear, reasonable, and agreeable to the experts.

Preparation of the Assessments and Written Rationale

The experts were instructed to use any information source available to assist them in the development of their distributions, such as analytical models, experimental data bases, etc., during the time between the first and second expert meetings. For each of the elicitation variables in the case structure, three percentile values, 5th, 50th, and 95th, from the cumulative distribution functions were requested from each of the experts with assessments of the absolute upper and lower bounds optional. A written rationale was also required from each expert so that the bases of the assessments could be traced.

Second Expert Meeting

On the first day, the experts presented their approaches and rationales to the project group without any numerical results to avoid biasing other experts. Starting from the second day, individual elicitation sessions were conducted. The composition of the elicitation team was modeled after the team structure implemented in NUREG-1150. Each elicitation team comprised one expert, a probability elicitor (normative analyst) whose main role was to assist the expert in encoding his judgments into consistent uncertainty distributions, and a member of the project staff (substantive assistant) whose main role was to answer any technical questions related to the project. Each expert was also provided an evaluation form at the end of the individual elicitation session to rate his experience participating in the project and voice any concerns and suggestions.

Processing the Elicited Results

Because multiple assessments were elicited without requiring consensus among them, the elicited assessments were aggregated for each elicitation variable. Although many different methods for aggregating expert judgments can be found in the literature, investigating alternative weighting schemes was not the objective of this joint effort. A programmatic decision was therefore made to assign all experts

Table ES-1 Atmospheric dispersion and deposition experts

Dispersion Experts	Country	Deposition Experts	Country
Pietro Cagnetti	Italy	John Brockmann	U.S.A.
Frank Gifford	U.S.A.	Sheldon Friedlander	U.S.A.
Paul Gudiksen	U.S.A.	John Garland	U.K.
Steve Hanna	U.S.A.	Jozef Pacyna	Norway
Jan Kretzschmar	Belgium	Joern Roed	Denmark
Klaus Nester	Germany	Richard Scorer	U.K.
Shankar Rao	U.S.A.	George Sehmel	U.S.A.
Han van Dop	Netherlands	Sean Twomey	U.S.A.

equal weight, i.e., all experts on each respective panel were treated as being equally credible. One of the primary reasons the equal weighting aggregation method was chosen for this study was to ensure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited from the experts, which would allow the application of performance based weighting schemes to the elicited dispersion and dry deposition results.*

The dispersion and wet deposition elicitation variables were not code input variables. It was therefore necessary to process the aggregated dispersion and wet deposition distributions into distributions over code input variables. Mathematical routines were designed so that the distributions developed for the code input variables would be consistent with the information contained in the aggregated elicited distributions.

Results and Conclusions

Uncertainty distributions were developed which represent state-of-the-art knowledge in the areas of atmospheric dispersion and deposition assessed by a most qualified group of experts. These distributions concern physically measurable quantities, conditional on the case structures provided to the experts. The experts were not directed to use any particular modeling approach but were free to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were developed by the experts from a variety of information sources. The aggregated distributions therefore include variations resulting from different modeling approaches and perspectives.

The aggregated elicited dry deposition distributions capture the uncertainty on the dry deposition velocity of particles of different sizes over different surfaces, while the aggregated elicited wet deposition distributions capture the uncertainty on the fraction of particles removed by rain. Because the dry deposition code input variables were physical quantities and were elicited directly from the experts, no further processing of the elicited dry deposition information was needed after aggregation of the individual assessments. A mathematical processing method developed in previous CEC-sponsored work was used to develop distributions over the wet deposition code input variables from the aggregated elicited wet deposition distributions. To verify the distributions generated for the wet deposition input variables, samples were taken from these distributions, propagated through the wet deposition code model, and the resulting distributions were found to well replicate the aggregated elicited wet deposition distributions.

The aggregated elicited dispersion distributions capture the uncertainty of the following quantities at several downwind distances: (1) the ratio of the plume centerline concentration relative to the source strength, (2) the standard deviation of the plume width in the cross-wind direction, and (3) the ratio of the off-centerline plume concentrations at specified locations in both the vertical and crosswind directions relative to the centerline plume concentration. Processing methods were developed based on the Gaussian plume model (GPM) implemented in the MACCS and COSYMA codes, as required in this joint study, to generate the corresponding code input variable distributions.

A portion of the aggregated elicited dispersion information was found to be inconsistent with the GPM because some dispersion experts thought it was possible for the off-centerline plume concentration to be higher than the centerline plume concentration for the sampling times specified in the case structure. In order to utilize and replicate the elicited information fully, modifications of the current code dispersion model, e.g., a smooth Gaussian profile superimposed with fluctuations, would be necessary. Such modifications were not possible in this project. Therefore, distributions over code input parameters were developed from that portion of the aggregated elicited distributions that were consistent with the GPM. To verify the distributions generated for the dispersion code input variables, samples were taken from these distributions, propagated through the GPM, and the resulting distributions were found to well replicate those aggregated elicited dispersion distributions consistent with the GPM assumptions.

Important lessons were learned in processing the elicited dispersion information. Given a fixed model, unless the code input variables happen to be physical quantities that can be elicited directly, such as in the dry deposition case an approach like that adopted in this exercise may result in complicated mathematical treatments to generate code input variable distributions. Moreover, when the elicited information clearly is incompatible with the fixed model, it is not apparent how to rationalize the distributions generated for the model parameters by using only information compatible

* A peer review panel of the NUREG-1150 study questioned the use of the equal weighting scheme without the consideration of other methods. Sufficient information was subsequently elicited in the present study to allow the application of alternative weighting schemes to the elicited data.

with the fixed model. In addition, a carefully designed case structure is crucial to ensure that important information needed to fully characterize the physical processes of interest is obtained from expert judgment elicitation.

Valuable information has been obtained from this exercise, despite the omission of uncertainties resulting from the non-Gaussian behavior of plumes. Because the aggregated elicited information is non-model-specific, it can also be fitted by other non-Gaussian analytical models. Thus, the goal of creating a library of atmospheric dispersion and deposition uncertainty distributions, which will have many applications outside of the scope of this project, has been fulfilled.

In this project, teams from the NRC and CEC were able to successfully work together to develop a unified process for the development of uncertainty distributions on consequence code input variables. Staff with diverse experience and expertise and from different organizations allowed a creative and synergistic interplay of ideas, which would not have been possible if they worked in isolation. Potential deficiencies in processes and methodologies were identified and addressed in this joint study, which might not have received sufficient attention in studies conducted independently. It is firmly believed that the final product of this study bears a more eminent credibility than either organization could have produced alone.

Furthermore, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle to synthesize the best available information by a most qualified group. With a thoughtfully designed elicitation approach addressing issues such as elicitation variable selection, case structure development, probability training, communication between the experts and project staff, and documentation of the results and rationale, followed by an appropriate application of the elicited information, expert judgment elicitation can play an important role. Indeed, it possibly becomes the only alternative technique to assemble the required information when it is impractical to perform experiments or when the available experimental results do not lead to an unambiguous and non-controversial conclusion. The distributions for the code input parameters are available on computer media and can be obtained from the project staff.

1. Background of Joint Program

1.1 Introduction

The development of two new probabilistic accident consequence codes—MACCS[1] in the US and COSYMA[2] in the European Communities (EC)—was completed in 1990, and both codes have been distributed to a large number of potential users. These codes have been developed primarily, but not solely, to enable estimates to be made of the risks presented by nuclear installations, based on the postulated frequencies and magnitudes of potential accidents. These risk estimates provide one of a number of inputs into judgments on risk acceptability and areas where further reductions in risk might be achieved at reasonable cost. They also enable comparisons to be made with quantitative safety objectives. Knowledge of the uncertainty associated with these risk estimates has an important role in the effective prioritization and allocation of research and development efforts toward the reduction of risk and the appropriate use of the results of risk assessments in regulatory activities.

This document describes an ongoing project designed to assess the uncertainty in the MACCS and COSYMA offsite radiological consequence calculations for hypothetical nuclear power plant accidents. Currently, the only uncertainty these codes are designed to calculate is the uncertainty caused by the stochastic variability of the weather. This project is designed to elicit from experts uncertainty distributions on important parameters that affect offsite radiological consequence calculations. The elicited distributions are to be used in consequence uncertainty analyses using the MACCS and COSYMA consequence codes.

Fairly comprehensive assessments of the uncertainties in the estimates of the radiological consequences of postulated accidental releases of radioactive material have already been made, both in the US and the EC, using predecessors of the MACCS and COSYMA codes (i.e., CRAC-2[3], MARC[4], and UFOMOD[5]). Fundamental to these assessments were estimates of uncertainty (or more explicitly, probability distributions of values) for each of the more important model parameters. In each case these estimates were largely made by those who developed the accident consequence codes, as opposed to experts in each of the many different scientific disciplines featured within an accident consequence code, e.g., atmospheric sciences, radioecology, metabolism, dosimetry, radiobiology, economics, etc. In addition, the underlying uncertainties in the submodels that constitute the consequence codes were not addressed.

The types of consequence uncertainty studies conducted prior to this project have suffered from two potential criticisms. First, much judgment is inevitably involved in the selection of important parameters, and their probability distributions and the basis for this have rarely been fully documented or justified. Second, the parameter selection, the assignment of probability distributions to these selected parameters, and the subsequent uncertainty analysis have largely been performed by the code developers, not by established experts in these areas.

The formal use of expert judgment has the potential to circumvent these criticisms. Although the use of expert judgment is common in the resolution of complex problems, it is most often used informally and rarely made explicit. The use of a formal expert judgment process has the considerable benefits of an improved expression of uncertainty, greater clarity and consistency of judgments, and an analysis that is more open to scrutiny. Formalized expert elicitation methods have been used in many studies such as performance assessment of the Waste Isolation Pilot Plant radiological waste repository,[6] performance assessments for high-level radioactive waste repositories,[7] the selection of sites for waste repositories, and assessments performed by the National Aeronautics and Space Administration.[8]

In terms of probabilistic nuclear accident analyses, formal expert elicitation methods were used extensively in the assessment of core damage frequency and radionuclide transport from the melt to the environment in the recent NUREG-1150[9] study of the risks of reactor operation. Their use was not without criticism or difficulties, but it was judged by a special review committee[10] to be preferable to the current alternative (i.e., risk analysts making informal judgments).

Within the EC, formal expert judgment has found increasing use in recent years, particularly by the European Space Agency[11] and in the Netherlands for a variety of studies. A pilot study in which the techniques were applied to one module of the COSYMA code (atmospheric dispersion and deposition) has recently been completed as a forerunner to the application of the techniques to the code overall.[12]

1.2 Establishment of Joint USNRC/ CEC Uncertainty Study

In 1991, both the Commission of European Communities (CEC) and the United States Nuclear Regulatory Commission (NRC) were giving consideration to initiating independent studies to better quantify and obtain more valid estimates of the uncertainties associated with the predictions of accident consequence codes. It was expected that the data acquired in such a study would significantly expand the knowledge and understanding of the strengths and weaknesses of current models, providing a basis and a direction for future research. In both cases the formal elicitation of expert judgment was intended to play an important role. It was recognized by both organizations that (given the similar purpose, scope, and content of both studies) several benefits could be gained from their integration. The primary advantages identified by the CEC and NRC for conducting a joint consequence uncertainty study are the following:

(1) To combine the knowledge and experience of the EC and US in the areas of uncertainty analysis, expert elicitation, and consequence analysis and to establish an internationally recognized probability elicitation protocol based on the NUREG-1150 probability elicitation methodology.

(2) To gain access to a greater pool of experts. The experts in the areas relevant to consequence calculations are located in both Europe and the United States. The joint project format presents an opportunity for the identification and utilization of a larger pool of world class experts than would be present in a project conducted solely by the US or EC.

(3) To capture the potentially greater technical and political acceptability of a joint project. Because of the different technical approaches of the two teams, there is the opportunity to consider alternative approaches together and to develop a final product which would be better than either team could produce in isolation.

(4) To share project costs. Expert elicitation projects require significant resources because of the staff resources and outside experts required for the exercise.

1.3 Objectives of Joint USNRC/CEC Uncertainty Study

The broad objectives of both the CEC and NRC in undertaking the Joint USNRC/CEC Consequence Code Uncertainty Study are:

(1) to formulate a generic, state-of-the-art methodology for uncertainty estimation which is capable of finding broad acceptance;

(2) to apply the methodology to estimate the uncertainties associated with the predictions of probabilistic accident consequence codes designed for assessing the consequences of commercial nuclear power plant accidents;

(3) to better quantify and obtain more valid estimates of the uncertainties associated with probabilistic accident consequence codes, thus enabling more informed and better judgments to be made in the areas of risk comparison and acceptability and therefore to help set priorities for future research.

Within these broad objectives, small differences in emphasis exist between the two organizations about how the results of the project may subsequently be used. The emphasis within the CEC is primarily on methodological development and its generic application, whereas the NRC, while sharing this interest, is also interested in the potential use of the methods and results as an input to the regulatory process. In particular, this would complement the work completed within the NRC-sponsored NUREG-1150 study, where the detailed analysis of the uncertainty in risk estimates was confined to consideration of the contributions arising from uncertainties in the probability, magnitude, and composition of potential accidental releases.

The ultimate objective of the NRC/CEC joint effort is to systematically develop credible and traceable uncertainty distributions for the respective code input variables using a formal expert judgment elicitation process. Each organization will then propagate and quantify the uncertainty in the predictions produced by their respective codes.

1.4 Development of Feasibility Study

Because of the magnitude and expense required to complete a full-scale consequence uncertainty analysis, the NRC and the CEC decided to first conduct a feasibility study. The two groups were interested in evaluating the feasibility of joint NRC/CEC projects, e.g., how easily project staff, located on different continents, could communicate and coordinate project details. The NRC and the CEC were also interested in determining if the technology required to develop uncertainty distributions for consequence code input parameters was developed fully enough to support this type of study. The feasibility study would evaluate a limited phenomenological area of consequence calculations.

The primary phenomenological areas that comprise a consequence calculation, which were identified as appropriate for consideration by a joint NRC/CEC study, are listed in Table 1.1. Other areas are also required for consequence calculations (emergency response, land interdiction, food interdiction, etc.). Distributions for the parameters in these areas were felt to be specific to the EC or the US and would not be developed jointly (methods developed in the joint project will be applied when performing these analyses).

Atmospheric dispersion and deposition parameters were chosen to be the focus of the initial feasibility study. The overall objective of the dispersion and deposition expert panels was to determine the efficacy and feasibility of the joint effort before expending the resources in the other areas relevant to consequence calculations (health effects, ingestion pathways, dosimetry, etc.). This objective included the following project goals:

(1) to develop a library of uncertainty distributions in the areas of radionuclide dispersion and deposition that could be used in many different consequence uncertainty studies using the MACCS and the COSYMA consequence codes;

(2) to evaluate the ability of teams from the CEC and NRC to work together effectively;

(3) to determine whether the technology exists for the development of credible uncertainty distributions on consequence code input parameters.

The reasons for choosing to address the uncertainty in atmospheric dispersion and deposition parameters for the initial feasibility study were:

(1) The dispersion and deposition parameters are high on a list of prioritized parameters generated for this study, based on past and contemporary sensitivity studies.

(2) The dispersion and deposition module is the first module in the calculus of endpoints of both codes.

(3) The CEC had performed a pilot study on these areas.

(4) It was expected that atmospheric dispersion and wet deposition would be two of the more difficult areas to analyze. The dispersion area is well studied but poses mathematical problems for the project staff in order to apply the elicited results to a consequence study. The deposition area is difficult because it requires the inte-

Table 1.1 Phenomenological areas that comprise a consequence calculation under consideration for joint study

Phenomenological Areas
Atmospheric dispersion of radionuclides
Deposition of radionuclides
Behavior of deposited material and calculation of related doses
Plume rise
Internal dosimetry
Early health effects
Late health effects
Food chain

gration of many different areas of physical science in an uncontrolled environment.

1.5 Project Ground Rules

The state-of-the-art approach developed in this study was formulated jointly based on two important ground rules: (1) the current code models would not be changed because both the NRC and CEC were interested in the uncertainties in the predictions produced by MACCS and COSYMA, respectively, and (2) the experts would only be asked to assess physical quantities which could potentially be measured in experiments.

Because of the restriction against the modification of MACCS and COSYMA, it is necessary to elicit distributions over consequence code input parameters or over variables from which distributions over code input parameters can be developed. In addition, the uncertainty distributions developed for the code input parameters could not contain values which could not be processed through the fixed models in the consequence codes.

Eliciting physical quantities avoids possible ambiguity in variable definitions. In addition, elicited variables that are physical parameters have the potential of not being tied to any particular analytical model and thus have a much wider application.

1.6 Brief Chronology of Joint Effort

July 1991 The first meeting between the CEC and the NRC was held in the US. The possibility of a joint consequence uncertainty project was discussed. The decision was made to proceed with the preparation of an outline specification to submit to CEC and NRC managements. In parallel to the preparation of the outline specification, supporting papers in the following three areas were written: 1) a recommendation for specific uncertainty and sensitivity methods; 2) a recommendation for expert elicitation methods; and 3) a recommendation for an approach for the prioritization of code input parameters.

Oct 1991 The second meeting between the NRC and the CEC was held in Europe. Further programmatic and technical details were discussed.

Jan 1992 The outlined specifications of the project were submitted to NRC management and CEC management along with the three technical recommendation papers (from July 1991). It was decided to perform the project in the following three stages: 1) assess the viability and efficacy of undertaking the work jointly; 2) prepare the detailed project description, including scope, content, timescales and costs; and 3) implement the project.

Apr 1992 An agreement was made between CEC management and NRC management to proceed to Stage 2 of the project (implementation planning stage).

May 1992 A general planning meeting was held in Brussels. The possibility of proceeding with one panel to demonstrate the efficacy and feasibility of the joint effort before proceeding with the remainder of the study was discussed.

Sum 1992 Initial thoughts on how to process the elicitation variables into code input variables in order to perform the uncertainty study were formulated.

Sept 1992 A decision was made to proceed with one panel to demonstrate the feasibility of the joint effort.

Nov 1992 Stage 2 was completed. The kickoff meeting for Stage 3 (implementation of the dispersion and deposition expert panels) was held in Europe.

Feb 1993 A working meeting was held in the US.

Mar 1993 Dry run of methods developed for project using dispersion and deposition experts from Sandia National Laboratories (US).

Apr 1993 Dispersion and deposition expert training meeting (Europe).

May 1993 Dispersion and deposition expert elicitation meeting (US).

Sep 1993 Processing meeting.

Dec 1993 Draft report.

May 1994 Final report.

June 1994 Technical appendices.

1.7 Design of Document

This report summarizes the achievements of the joint effort. Chapter 2 of this report provides a discussion of the technical issues that were considered prior to the actual expert elicitation process. Chapter 2 provides a brief history of consequence uncertainty studies, describes why uncertainty information is necessary for decision making, summarizes the MACCS and COSYMA codes, describes the process used for selecting the variables that were assessed, explains why formal expert elicitation methods were chosen, and delineates the scope of the project.

Chapter 3 summarizes the methods used for acquiring the distributions for the elicitation variables and the processing of the distributions into a form usable by MACCS and COSYMA (a more detailed discussion of the methods is presented in Appendices C, D, and E). Results are summarized in Chapter 4, and conclusions are presented in Chapter 5.

Volumes II and III of this report contain the technical appendices. The rationale provided by each expert and the raw (unprocessed) data received from the experts are provided in Appendix A. Brief biographies of the experts are presented in Appendix B. Appendices C through H contain methodological information.

1.8 References

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2. Technical Issues Considered Prior to Initial Feasibility Study

2.1 Introduction

Uncertainty analysis was introduced into a broad decision-making context with the Reactor Safety Study (WASH-1400).[1] Although the techniques have undergone considerable development since this study, the essentials have remained unchanged. The intent of uncertainty analysis is to quantify the uncertainty in the output of quantitative decision support modeling in order to provide the decision maker with a measure of how robust or accurate the conclusions are, based on the model. To accomplish this, distributions are placed on the parameters of models and propagated through the model to yield distributions on the model's output.

Uncertainty analysis is typically performed in situations in which the uncertainties in model predictions have the potential to significantly impact the decision-making process and "stakeholders" have differing interests and perceptions of the risks and benefits of possible decisions. There is no formula dictating how the results of quantitative models should be used to support such decision making; hence, there can be no formula for the use of uncertainty analyses either. Rather, uncertainty analysis provides a tool with which stakeholders can better express their pros and cons. In this sense, uncertainty analysis can contribute to a rational discussion of proposed courses of action. As a collateral benefit, uncertainty analysis provides a perspective for assessing the quality of the quantitative decision-support modeling and can help direct resources for reducing uncertainties in the future.

Uncertainty analyses using expert elicitation techniques have been performed for the Level 1 (core damage frequency assessment) and Level 2 (assessment of radionuclide transport from the melt to the environment) portions of risk assessments. Uncertainty/sensitivity analyses for the Level 3 (consequence analysis) portion of risk assessment have primarily consisted of parametric sensitivity studies in which uncertainty distributions of code input parameters are sampled and the impact of different input parameter values on model output is observed. In these studies, the uncertainty distributions for the input parameters were developed primarily by the code developers and not by experts in the many different scientific disciplines that constitute the consequence calculations.

This chapter defines types of uncertainty, presents a brief history of uncertainty analysis in the area of probabilistic nuclear accident consequence analysis, explains why uncertainty analysis is sometimes needed, and sketches the methods and issues that arise in carrying out an uncertainty analysis for accident consequence models.

2.2 Types of Uncertainty

The NRC Probabilistic Risk Analysis (PRA) Working Group[2] has defined two types of uncertainty which may be present in any calculation. These are (1) stochastic uncertainty caused by the natural variability in a parameter and (2) state-of-knowledge uncertainty, which results from a lack of complete information about systems, phenomena, or processes. State-of-knowledge uncertainty may be further divided into (1) parameter uncertainty, which results from a lack of knowledge about the correct inputs to analytical models; (2) model uncertainty, which is a result of the fact that perfect models cannot be constructed, and (3) completeness uncertainty, which refers to the uncertainty as to whether all the significant phenomena and relationships have been considered.

Stochastic uncertainty is inherent in the physical process involved and therefore cannot be reduced. Although additional data cannot reduce the stochastic uncertainty, they can provide information about the probability distribution of the stochastic uncertainty. An example of stochastic uncertainty is the natural variability of the weather.

Probabilistic models require the input of parameter values, which are utilized to calculate results. Parameter uncertainty arises because we rarely know with complete certainty the correct value of the input parameters. This lack of complete knowledge of correct input parameters will contribute to the uncertainty in the model predictions.

In regards to modeling uncertainty, the PRA Working Group document states that:

> Models of physical processes generally have many underlying assumptions and often are not valid for all possible cases. Often there are alternative models proposed by different analysts, and it is not known which, if any, of the models is the most

appropriate one (each alternative will have its own deficiencies).

The PRA Working Group document defines completeness uncertainty as the following:

> Completeness uncertainty is similar to modeling uncertainty, but occurs at the initial stage in an analysis. In addition to inadequate identification of the physical phenomena, completeness uncertainty can also result from inadequate consideration of human error, software reliability or interactions and dependencies among the element of the process being modeled. Some practitioners consider completeness uncertainty as a subset of model uncertainty.

A common method of uncertainty analysis is based on the propagation of a distribution over an input parameter through a model, rather than a point value for a parameter. The distributions for the code input parameters can be developed from a number of sources, e.g., phenomenological models, experimental data, or a combination of different models and experimental data. In the past, distributions over code input parameters have typically been developed by code developers with informal guidance from phenomenological experts or through a formal process of eliciting distributions from phenomenological experts in the appropriate field. The resulting distribution over the model output provides insight regarding the impact of input parameter uncertainty on model predictions.

An uncertainty analysis may also be performed by propagating the same input data through different analytical models and observing the variation in predictions that are produced by the different models. This type of uncertainty analysis would provide information relating to modeling uncertainty and could also be designed to provide information relating to completeness uncertainty.

2.3 Brief History of Consequence Uncertainty Analyses

For over a decade, the CEC and the NRC have supported research into the uncertainty analysis of nuclear probabilistic accident consequence codes (ACC). This section briefly reviews the development of uncertainty analysis in the field of nuclear probabilistic accident consequence analysis.

2.3.1 History of US Consequence Uncertainty Analyses

The Reactor Safety Study (WASH-1400)[1] was completed by the NRC in 1975. Although this study was highly praised by the technical community, it was criticized for providing an incomplete characterization of the uncertainty in its results.[3] As a result, when the NRC initiated a program at Sandia National Laboratories (SNL) in the late 1970s to develop a methodology to assess the risk associated with the geologic disposal of radioactive waste, the development of techniques for uncertainty and sensitivity analysis was given a high priority.

This development program emphasized uncertainty and sensitivity analysis techniques based on Latin Hypercube Sampling (LHS)[4] and the subsequent exploration of the resultant mapping from analysis inputs to analysis results with regression-based techniques.[5,6,7,8,9] Several useful pieces of software emerged from this program, including the LHS program[10] for generating Latin Hypercube and random samples, the STEP program[11] for stepwise regression analysis and the PCCSRC program[12] for partial correlation analysis. The Iman/Conover technique[13] for the incorporation of rank correlations into Latin Hypercube and random samples was also developed during this period. This period produced a number of examples of the application of uncertainty and sensitivity analysis techniques to problems related to the geologic disposal of radioactive waste.[14,15,16,17]

The previously indicated techniques were then applied to the study of early and chronic cancer fatalities with the CRAC2[18] reactor accident consequence model. The purpose of this study was primarily to determine if techniques based on LHS and regression analysis would be effective in analyses with reactor accident consequence models. The techniques were effective and the outcomes of this analysis are documented in several publications.[19,20,21]

The MELCOR project was initiated in the early 1980s to develop a new suite of computational tools to support the calculation of the consequences associated with severe reactor accidents, including uncertainty and sensitivity analysis.[22] As part of this project, available uncertainty and sensitivity techniques (i.e., differential analysis, response surface methodology, Monte Carlo analysis, Fourier amplitude sensitivity testing) were reviewed and compared.[23,24,25] These comparisons with several different models again showed uncertainty and sensitivity analysis procedures based on LHS to be quite effective in the analysis of the uncertainty associated with complex models. The MACCS program[26,27,28] was also developed as part of the MELCOR code systems.

In the mid 1980s the NRC initiated a followup to the WASH-1400 study that has come to be known a NUREG-1150 after its associated report number.[29] Among the charters was for NUREG-1150 to provide a representation for the uncertainty in its results and, in particular, to counter the criticism that WASH-1400 had inadequately represented the uncertainty in its results. To meet this requirement, NUREG-1150 used techniques based on LHS and an extensive expert review process to characterize the uncertainty in important input parameters.[30,31,32,33,34,35,a,b,36] In particular, uncertainty and sensitivity studies were performed for the systems analysis, accident progression analysis, and source term analysis components of the probabilistic risk assessments conducted for the Surry,[37,38,39,40] Peach Bottom,[41,c,42,43] Grand Gulf,[44,45,46] Sequoyah,[47,48,49] and Zion[50,51] nuclear power stations. No attempt was made to incorporate the effects of the uncertainty in the consequence analysis component of these probabilistic risk assessments into the overall analysis outcomes. However, to provide possible guidance on how to incorporate such uncertainties, one sampling-based uncertainty/sensitivity study of early health effects was performed with the MACCS code, version 1.4.[52,53] In the end, though, no attempt was made to incorporate consequence modeling uncertainty into the NUREG-1150 results. The same is also true of a recent research program on probabilistic risk assessment techniques that used the LaSalle nuclear power station as an example.[54] An example of the application of uncertainty analysis results from NUREG-1150 to reactor-accident safety goals is provided in the references.[55]

Subsequent to NUREG-1150, concern about the uncertainty in consequence analysis results has led to three uncertainty/sensitivity studies with MACCS.[d,e,f] These studies are very much in the spirit of the uncertainty/sensitivity studies conducted at SNL and Los Alamos National Laboratory and employ techniques based on LHS and regression analysis. The first study considers the early health effects associated with a severe accident; the second and third studies consider food chain and chronic exposure results, respectively. In these uncertainty/sensitivity studies, only the uncertainties in code input parameters were considered, and the distributions over the code input parameters were primarily developed by the code developers.

An important theme that has emerged in the treatment of uncertainty in performance assessments for complex systems is the requirement on the part of the customers to separate the uncertainty that arises from the behavior of the systems (i.e., stochastic uncertainty) and the uncertainty that arises from a lack of knowledge on the part of the individuals modeling the system (i.e., state of knowledge uncertainty).[56,57,58,59,60,61,62] This is an extremely complex subject, and the division of uncertainty into different types of uncertainty is not always clear. Attempts have been made to maintain this distinction in the NUREG-1150 analyses,[40,63,64] several recent MACCS analyses,[41,c,42] and the Waste Isolation Pilot Plant performance assessment.[43,65] An overview of these analyses and the manner in which these two types of uncertainty are treated within them is provided in Helton.[g]

2.3.2 History of European Consequence Uncertainty Analyses

In the CEC, work began with the development of uncertainty and sensitivity analysis methodologies for nuclear ACCs. Uncertainty analyses of nuclear ACCs were first performed in 1979/80 within the German Risk Study-Phase A.[66,67] Uncertainty propagation methods developed by the German Institute for Reactor Safety (GRS) were applied to the UFOMOD code.[h] Consequence uncertainty analyses

[a] Harper, F.T., et al., Sandia National Laboratories, "Evaluation of Severe Accident Risks: Quantification of Major Input Parameters: Supporting Material," copy available in the NRC public document room.

[b] Harper, F.T., et al., Sandia National Laboratories, "Evaluation of Severe Accident Risks: Quantification of Major Input Parameters: Determination of Parameter Values Not Quantified by Expert Panels," copy available in the NRC public document room.

[c] Lambright, J.A., et al., Sandia National Laboratories, "Analysis of Core Damage Frequency: Peach Bottom, Unit 2 External Events," NUREG/CR-4550, SAND86-2084, Vol. 4, Rev. 1, Pt. 3, Albuquerque, NM, December 1990.

[d] Helton, J.C., et al., Sandia National Laboratories, "Uncertainty and Sensitivity Analysis of Early Exposure Results with the MACCS Reactor Accident Consequence Model," NUREG/CR-6135, SAND93-2371, Albuquerque, NM, December 1994

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[f] Helton, J.C., et al., Sandia National Laboratories, "Uncertainty and Sensitivity Analysis of Chronic Exposure Results with the MACCS Reactor Accident Consequence Model," NUREG/CR-6134, SAND93-2370, Albuquerque, NM, December, 1994.

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became an important part of the probabilistic nuclear accident R&D work in the CEC with the start of the CEC Methods for Assessing the Radiological Impact of Accidents (MARIA) research program in 1983. The German Nuclear Research Center Karlsruhe (KfK), the GRS, and the National Radiation Protection Board (NRPB) in the UK were the major contractors involved in the MARIA program. Uncertainty analyses of particular code modules were considered. These analyses were limited to an analysis of the uncertainty in code input parameter values. The uncertainties were largely specified by the code developers rather than phenomenological experts in the appropriate fields.

As part of the MARIA program, KfK published several studies on uncertainty and sensitivity analysis with submodules of UFOMOD and the overall program system. The main objective of the KfK work was to apply LHS methods to the quantification of the uncertainties of intermediate and final results of consequence assessments of significant releases of radioactive material in the near range and in the early phase of an accident. An additional objective of this study was to identify the most important parameters contributing to these uncertainties. Results have been published in several KfK contributions[i,68,69,70] and are best summarized in Fischer et al.[71]

The NRPB performed uncertainty analyses on accident consequence modeling in the MARC code and on the related area of deposited gamma dose in urban areas (both mostly under the MARIA program). The MARC uncertainty analyses were performed in three phases. The first stage separately examined the uncertainty in the atmospheric dispersion and food chain modules, AD-MARC and FOOD-MARC, respectively.[68] In the AD-MARC analysis, the uncertainty on air concentration and deposition at various points was considered. In the FOOD-MARC analysis, the amounts of food banned and the doses from food were considered. In the second stage, LHS methods were applied, and the uncertainty of MARC-predictions of numbers of health effects resulting from the uncertainty in the deposition and dispersion parameters was analyzed.[72] The work in the third stage considered 98 input parameters—covering the calculation of dispersion, deposition, food chain modeling, dosimetry, health effects, and economic costs—to be uncertain.[70] The results were presented in terms of uncertainties in number of health effects, extent of countermeasures, and economic costs of accidents. In the third stage, the deposited gamma dose uncertainty study was carried out using the EXPURT code, which calculates gamma doses from material deposited in an urban area.[73] In all cases, the input parameters whose uncertainty made a major contribution to the overall uncertainty were identified.

The GRS was involved in the first major uncertainty study in Europe, the German Risk Study[74] and participated in uncertainty studies with the KfK and the NRPB.[75] Subsequently, the GRS developed a software system for uncertainty and sensitivity analysis (SUSA) for mainframe and personal computers (sponsored by the CEC and the German Federal Ministry for Research and Technology). The system has been used for the analysis of code applications in a variety of disciplines, including atmospheric dispersion[76] and radiological consequences.[77]

In 1990 the CEC, as part of the MARIA program, sponsored a pilot study conducted at Delft University in the Netherlands, which tested the use of structured expert judgment in the assessment of uncertainty in the MARIA accident consequence code, COSYMA. This pilot study was the first attempt to apply expert judgment techniques to the consequence area. The pilot study focused on the dispersion and deposition modules, MUSEMET and COSGAP. The pilot study utilized only European experts and did not attempt to completely cover the domain which would be required for a complete uncertainty analysis of the dispersion and deposition modules in COSYMA.

2.3.3 Lessons Learned from Past Uncertainty Analyses

Many important lessons have been learned from past uncertainty studies. Distributions for code input parameters developed informally by code developers typically have smaller uncertainty bands than distributions developed using formal methods by phenomenological experts in the appropriate field. Uncertainty studies that elicit data from panels of phenomenological experts have more credibility if the expert selection process is a documented objective process that results in the representation of the full range of professional opinion and modeling perspectives on the panel. Also, analytical models are only approximations of physical phenomena; therefore, the entire range of uncertainty in model predictions cannot by captured solely by the development and utilization of distributions over model

[h] UFOMOD was developed to estimate the offsite consequences of potential severe accidents at nuclear power plants. It is a predecessor to the COSYMA code.

[i] Ehrhardt, J., and F. Fischer, "Uncertainty and Sensitivity Analyses of UFOMOD," *DOE/CEC Workshop on Uncertainty Analysis in Accident Consequence Assessments, 13-16 November 1989*, Santa Fe, NM, USA.

input. However, the uncertainty range of model predictions is more accurately represented when distributions over model input parameters are developed by combining information from all relevant sources rather than from a single model or information source.

In addition, past uncertainty studies have shown that the uncertainty captured in distributions must be precisely defined and consistently communicated and represented in the model. A lack of clarity can produce inconsistent results. Elicitation on measurable parameters, rather than theoretical or mathematical constructs that do not directly represent physical phenomena, reduces the potential for ambiguity in the definition of the elicitation variables and the types of uncertainty contained in the distributions over these variables.

Uncertainty analyses to date have demonstrated large uncertainty ranges in model predictions, indicating that for some applications point value estimates may be of little value in the decision-making process. Point values for phenomena for which large uncertainties are known to exist lack credibility without information relating to the uncertainty band for the model predictions. Finally, past studies have indicated that it can be very difficult to communicate model predictions in terms of uncertainty distributions to decision makers. Decision makers have often relied on deterministic, best estimate predictions and may find it difficult to think in terms of uncertainty. Training can facilitate the transition from decision making based on single point estimates to decision making within the context of uncertainty.

2.4 When Should Uncertainty Analysis Be Performed?

Uncertainty analysis is indicated when each of the following is present:

- decision making is supported by quantitative model(s),
- the modeling is associated with potentially large uncertainties,
- the consequences predicted by models are associated with utilities and disutilities in a non-linear way (threshold effects are the most common example),
- the choice between alternative courses of action might change as different plausible scenarios are fed into the quantitative models,
- the scenarios of concern are low probability, high consequence events.

A simple example illustrates these features. Suppose a power company must choose between the construction of a fossil fuel plant or a nuclear power plant based on the public health risk of each technology. Assume models are available that calculate the public health risk based on a function of factors such as releases of pollutants during normal operations and accident events, the probability of accidental releases, and the health effects of environmental pollutants. If these factors were known with certainty and if the models which calculate public health risk were known to be correct, there would be no uncertainty in the models' output, and no need for uncertainty analysis. Even though the above factors are not known with certainty, it might be argued that the *expected* pollutant released and the *expected* health effects could be fed into the models to yield the *expected* public health risk (strictly speaking, this could be guaranteed only if the models were linear in the input variables). However, if a large number of people suffer (unexpected) health effects from plant emissions, there is a likelihood that the plant would not be allowed to continue operation. Different possible scenarios have the potential of producing a range of health effects for which our state of knowledge may be incomplete. A possible scenario may present risks to public health that are unacceptable to the public. Further rational deliberation of alternatives now requires identifying the possible scenarios, quantifying the probability of each scenario, and running each scenario through the models to yield a distribution over possible health risks associated with each technology. This is uncertainty analysis. Notice that uncertainty analysis does not solve the decision problem. It is clear, however, that uncertainty analysis is an essential ingredient to responsible decision making when the features listed above apply.

In a regulatory context, we are not dealing with a full decision problem. The regulatory authority is typically charged with regulating the risks from one type of activity. The choice between alternatives is made at a different level, where the trade-off of utilities against disutilities of different stakeholders are factored in. It is, nonetheless, incumbent upon the regulatory authority to provide such information as is deemed necessary for responsible decision making. In the broad energy policy debate, it has long been acknowledged that the features mentioned above apply. Nuclear regulatory agencies have pioneered the use of uncertainty analysis and continue to set the standards in this field.

2.5 How Is an Uncertainty Analysis Performed?

The uncertainty information obtained and processed in this joint effort is expressed as variability in code input parameters. An uncertainty analysis of this type may be broken into three steps:

- assessing uncertainty over the code input,
- propagating uncertainty through the code,
- communicating results to decision makers.

A brief discussion of each step is presented below.

2.5.1 Assessing Uncertainty over Model Input

Accident consequence codes involve a large number of parameters. These include parameters describing the transport of released contaminants, parameters describing the absorption of contaminants by people, and parameters describing health effects and economic damages. Few of these parameters are known with certainty, yet it is not currently feasible to quantify uncertainty for all parameters. Hence, a preliminary sifting is performed to identify those parameters whose uncertainty can contribute significantly to uncertainty in the accident consequence predictions.

A sensitivity study is performed in order to identify the code input parameters that have the greatest impact on the code accident consequence predictions. Once a set of potentially important parameters has been identified, uncertainty over these parameters must be quantified. This is done by assigning (joint) probability distributions to the parameters. When sufficient statistical data are available, these are used to generate distributions. When statistical data are not available, uncertainty is quantified via subjective probability distributions.

The use of subjective probabilities is a central theme in uncertainty analysis. The method for generating and using subjective probabilities has undergone substantial development in recent years, and the current study has incorporated many significant advances in this respect. Trained elicitors obtain subjective probability distributions from experts who are selected according to a fully traceable method and have been trained in assessing subjective probabilities. Distributions are elicited from experts over variables that have clear empirical interpretations; elicitation variables may be thought of as possible outcomes of hypothetical physical experiments. Information is provided to the experts regarding the hypothetical physical experiments that correspond to the physical context in which the models are to be applied. Defining the hypothetical experiment to correspond with the context of the code model helps to ensure compatibility between the elicited distributions and the code model. The distributions obtained from each expert for each elicitation variable are combined to form an aggregated distribution for each elicitation variable.

2.5.2 Propagating Uncertainty through the Code

When probability distributions have been obtained on the code parameters, these distributions must be propagated through the code. In very simple cases this can be done analytically. For example, if the code is simply the sum of two quantities, and if the uncertainty on each quantity is described by (independent) normal distributions, then the distribution of the sum is known to be normal with mean and variance equal to the sum of the means and variances of the individual distributions. In practice the codes to be analyzed are much more complex, and analytic solutions are not available.

For complex codes, the distribution over code output is determined by simulation. To perform one simulation run, a value for each parameter is drawn from the appropriate uncertainty distribution, the code is run with these parameter values and the result is stored. This process is repeated many times until a distribution over the code output is developed. Many important technical issues must be addressed to implement this process. These issues include:

- how values are sampled efficiently from the parameter distribution,
- how dependencies among parameter distributions are processed, and
- how the assessment is made of the contribution to the output uncertainty from the uncertainty over each parameter.

2.5.3 Communicating Results to Decision Makers

Accident consequence codes compute many quantities of interest (or "endpoints") including time varying radiation levels over a large spatial grid, numbers of acute and chronic fatalities, number of persons evacuated, amount of land denied, economic and environmental damages. In the point value mode of calculation, the consequence codes compute distributions over these quantities resulting from uncertainty in meteorological conditions at the time of the accident. In performing a full scope uncertainty analysis, distributions over code parameters other than weather parameters are generated for each quantity. The question of how best to compress the information into a form that can be used by decision makers receives considerable attention.

In some applications of the information, it may be important for the decision maker to distinguish statistical uncertainty resulting from variation in meteorological conditions or other sources from state-of-knowledge uncertainty over code parameters. Statistical uncertainty is here to stay, whereas state-of-knowledge uncertainty may change as knowledge grows; distinguishing between the statistical and state-of-knowledge uncertainty could be helpful in research prioritization.

For allocating future research resources, it is important to know the contribution of each parameter's uncertainty to the overall uncertainty and to identify those parameters for which uncertainty can be significantly reduced by future research efforts.

2.6 Brief Description of MACCS and COSYMA Dispersion and Deposition Models

The uncertainty distributions developed in this study will be used to perform uncertainty studies using the CEC consequence code COSYMA and the NRC code MACCS. COSYMA and MACCS model the offsite consequences of postulated severe reactor accidents that release a plume of radioactive material to the atmosphere. These codes model the transport and deposition of radioactive gases and aerosols into the environment and the potential resulting human health and economic consequences. These codes are typically used as part of a probabilistic assessment of risk. For this reason, the meteorological conditions at the time of release are varied by sampling over historical data. This sampling allows the inclusion of the uncertainty in meteorological conditions at the time of the accident in the calculation.

This section reviews the dispersion and deposition models implemented in MACCS and COSYMA and the code input parameters required by these models for which uncertainty distributions were developed in this study.

2.6.1 The Gaussian Plume Model

Under the assumption of constant wind direction, no plume rise and no precipitation, most atmospheric dispersion models, including those in COSYMA and MACCS, are effectively identical. The atmospheric dispersion model used in the codes is the Gaussian plume model (GPM). Taking x as the downwind distance, y as the crosswind direction and z as the vertical direction, the time integrated concentration [Bq s/m^3] at the point (x,y,z) is given as[78]

$$\chi(x,y,z) = \frac{Q_0}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left\{\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right\} \tag{2.1}$$

where:

Q_0 is the initial quantity of material released [Bq]

$\bar{u}$ is the mean wind speed (always in the x-direction) [m/s]

H is the height of the plume centerline [m]

σ_y, σ_z are the diffusion coefficients in the y and z directions. The values of these parameters depend on the atmospheric stability class and on the surface roughness.

The straight-line GPM is strictly applicable in only a limited range of atmospheric and environmental conditions, because for its derivation it is assumed that the terrain over which the material is dispersing is uniform and that atmospheric conditions are constant. The restricting assumptions of stationary and homogeneous turbulent diffusion are partly compensated by using diffusion parameters, σ_y and σ_z, which are determined experimentally. Mathematically, these parameters are the lateral and vertical standard deviations of the assumed Gaussian concentration distribution.

Physically, they describe the crosswind and vertical extension of the plume at downwind distance x. The purpose of the last term of Equation (2.1) is to account for reflection of the plume at the ground by assuming an imaginary source at distance H beneath the release height. A minimum wind speed of u = 0.5 m/s is assumed for calm wind conditions.

2.6.1.1 Diffusion Coefficients

The diffusion coefficients, σ_y and σ_z, depend heavily on the meteorological conditions. In the past, researchers used stability classification schemes to determine what kind of weather was considered. The most widely used scheme was developed by Pasquill and slightly modified by Turner (see Table 2.1). In general, stability classes A through C represent unstable conditions, class D represents nearly neutral conditions, and classes E and F represent stable conditions.

However, if turbulence measurements are available, it is preferable to estimate σ_y and σ_z by using σ_θ and σ_e, standard deviations of wind direction fluctuations in the horizontal and vertical directions, respectively. The basic turbulence typing methods are compared in Table 2.2. The fact that these divisions and comparisons are arbitrary is important, and this system should not be considered perfect.

Several researchers have developed analytical power law formulas for σ_y and σ_z. Commonly the diffusion coefficient, represented as a power law, is assumed to be a function of travel distance.

$$\sigma_z = a_y x^{b_y} \tag{2.2}$$

$$\sigma_z = a_z x^{b_z} \tag{2.3}$$

Table 2.1 Meteorological conditions defining Pasquill turbulence types

A: Extremely unstable conditions	D: Neutral conditions
B: Moderately unstable conditions	E: Slightly stable conditions
C: Slightly unstable conditions	F: Moderately stable conditions

	Daytime insolation			Nighttime conditions	
Surface wind speed, m/sec	**Strong**	**Moderate**	**Slight**	**Thin overcast or > 4/5 low cloud**	**< 3/8 cloudiness**
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-4	B	B-C	C	D	E
4-6	C	C-D	D	D	D
>6	C	D	D	D	D

From Pasquill and Smith[79]

Table 2.2 Relations among turbulence typing methods

Stability description	Pasquill	Turner	BNL	σ_θ, deg (at 10 m)
Very unstable	A	1	A	25
Moderately unstable	B	2	B_1	20
Slightly unstable	C	3	B_2	15
Neutral	D	4	C	10
Slightly stable	E	6		5
Moderately stable	F	7	D	2.5

From Gifford[80]

In the MACCS and COSYMA consequence codes, a_y, b_y, a_z, and b_z are code input parameters from which values for σ_y and σ_z are calculated. In general the parameters of the diffusion coefficients a_y, b_y, a_z, and b_z depend on the surface roughness and on the stability class. The values for these parameters are determined by tracer experiments for different meteorological conditions, different release heights, and different conditions of the underlying surface. MACCS and COSYMA contain algorithms that define the occurrence of a uniform concentration distribution in the vertical direction (a well mixed plume between the ground and the capping inversion layer) at which point χ/Q_0 is no longer a function of σ_z.

2.6.2 Dry Deposition

Dry deposition incorporates removal from the plume by diffusion, impaction, and settling and is modeled using a dry deposition velocity, which is the dry deposition user input parameter for MACCS and COSYMA. The time integrated surface contamination $\chi(x,y,0)$ [Bq/m^2] at the point $(x,y,0)$ caused by contact between the plume and the ground is defined as

$$\chi_d(x,y,0) = v_d \chi(x,y,0) \tag{2.4}$$

where v_d is the dry deposition velocity, defined as

$$v_d = \frac{\text{mass flux}}{\text{concentration}}. \tag{2.5}$$

Concentration is typically considered at one meter above the ground. The units are those of velocity as

$$\frac{(\text{g/s m}^2)}{(\text{g/m}^3)} = \frac{\text{m}}{\text{s}}. \tag{2.6}$$

From the above equations it can be seen that ground contamination is linear in deposition velocity: doubling the deposition velocity would double the contamination. This parameter is therefore very critical for determining the consequences of a release.

The physical modeling of dry deposition for aerosol particles is somewhat simpler, and somewhat more successful, than for gases. The reason is that chemical properties of the airborne material and of the host surface strongly influence the deposition of gases, whereas the deposition of particles is dominated by the physics of momentum transfer.

The dry deposition process for aerosols is conceived in the following terms. Surfaces are covered with a thin boundary layer of effectively motionless air. Particles can deposit on the surface only if they have sufficient velocity to overcome the resistance of the inert air and cross this boundary layer. The modeling of deposition for small particles assumes that the mean velocity normal to the surface is imparted principally by Brownian motion. Factors like humidity, temperature, and electrostatic gradients may be of influence in this regime but have not been incorporated in the modeling. Velocity from Brownian motion increases with decreasing particle size until the size of gas molecules is reached. For large particles, velocity normal to a surface is imparted by turbulent eddys in the atmosphere and by gravitational settling.

Between the two regimes of Brownian motion and turbulence/gravitational settling, the rate of deposition is influenced by a great many factors and the physical modeling becomes more speculative. Sehmel[81] has listed some 80 factors known to play a role. Humidity plays a large role when relative humidity exceeds 90%.[82] Fine structure of the vegetation canopy can be very important. In neutral conditions, deposition to different species of grass has been found to vary over an order of magnitude.[83] Time of day is also critical for this effect.

Because of its strong variability between the regimes of Brownian motion and gravitational settling, many authors have argued for including particle size distribution in the consequence codes so that dry deposition can be handled differently for different particle sizes. Current codes require one value for the dry deposition velocity for aerosols, which is normally taken for particles with an aerodynamic diameter of 1 μm^2. As pointed out by Cooke,[84] arguments for this choice are based on the fact that the smallest deposition velocities occur for diameters of about this size, hence this diameter will dominate. In some experiments, 40% of the deposited mass comes from the largest 10% of airborne particles. [83] For this reason the mass average diameter was recommended in the CEC Pilot Study, instead of the particle diameter mode. A discussion of the effects of including particle size distributions is given in Cooke.[84]

2.6.3 Wet Deposition

When rain passes through a plume, material is deposited via the mechanism of wet deposition:

$$\chi_w(x,y,0) = \Lambda \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \tag{2.7}$$

where $\Lambda[s^{-1}]$ is the "washout coefficient," assumed to be constant in space and time. Field measurements for Λ are all but impossible, and laboratory measurements tend to exhibit an order of magnitude spread because of the difficulty of controlling such variables as drop size and drop collection efficiency, drop size distribution, and drop velocity. Collection efficiency in particular is known to depend strongly on electric charge; charges characteristic of thunderstorms increase collection efficiency by some two orders of magnitude. In accident consequence codes the washout coefficient is modeled simply as a power law function of rain intensity (I):

$$\Lambda(I) = a_\lambda I^{b_\lambda} \, . \tag{2.8}$$

The wet deposition code input parameters for MACCS and COSYMA are the a_λ and b_λ parameters of the washout coefficient power law.

2.7 Selection of Variables to Be Presented to Formal Expert Elicitation Panels

Because the resources required to develop distributions for elicitation variables using a formal elicitation process are relatively high, it is critical to select those variables for elicitation that are most important to consequence uncertainty. Exclusion of variables from the list of those to be formally elicited does not mean they are to be excluded from the analysis. The uncertainty in these variables will be evaluated by less resource-intensive methods, e.g., literature searches, consequence analyst judgement, etc. Thus the prioritization procedure, while important in terms of ensuring effective utilization of resources, is not critical in terms of excluding the contribution of potentially important variables.

The elicitation variables were chosen systematically using the method outlined below.

(1) Sensitivity studies using MACCS in the US and UFOMOD in the EC were performed. Lists of code input variables that were shown to be important to the different consequence measures were generated independently by the US and EC. Lists of important code input variables were generated for both prompt and latent consequences. As an example, the US list is summarized in Table 2.3. Sensitivity studies from the US relied on traditional regression techniques and additional parametric importance assessment techniques developed at Los Alamos National Laboratories specifically for this program to prioritize code input variables.[85]

(2) A team of US and EC consequence experts developed a joint list of important code input parameters from a review of the lists generated from the sensitivity studies performed in the US and the EC. The joint list of important code input parameters is presented in Table 2.4.

(3) It was not considered feasible to jointly assess code input variables that are highly specific to conditions in the EC or in the US. For this reason, any variables related to policy or economics were eliminated from consideration by the joint study (evacuation policy, food interdiction criteria, and costs of countermeasures are all examples of these variables). For the purposes of the uncertainty calculations, these variables will be assessed independently by the CEC and NRC using the methods developed in the joint project.

(4) If there were any analytical or experimental alternatives to obtaining defensible distributions for any of the code input variables, the variable in question was dropped from the list of assessed elicitation variables using expert judgment techniques. The selected variables subsequently represent only parameters for which insufficient experimental data are available for developing uncertainty distributions over the parameters. Some of the reasons for lack of sufficient experimental evidence could be unacceptable costs and lack of technology.

(5) From the final list of code input variables, elicitation variables that were experimentally observable were selected or developed. The experimentally observable constraint was inserted for two reasons (a) to avoid ambiguity when presenting the definition of the elicitation variables (if the experts assess poorly defined variables, the potential for incompatible assessments is high) and (b) to ensure the elicited distributions are applicable beyond the context of the present study.

In many cases, the experimentally observable constraint resulted in elicitation variables that were the output of specific sub-models rather than the code input variable in the sub-models. The distributions obtained by eliciting only on

Table 2.3 Code input variables for prompt and latent consequences

Important Code Input Variable	Proposed Expert Panel	Important to Early or Chronic Consequence Measures	Factors that Should be Considered in Elicitation Design	Comment
Power law parameters that define the standard deviation of the plume in the cross-wind direction*	Dispersion	Dominant to early consequences; important to chronic consequences	X, Y, Z coordinates Windspeed Stability Surface roughness (in conjunction with deposition velocity)	Contribute more to high values of early fatalities in stable weather (when standard deviation of plume is small)
			Discreet rain intensity (in conjunction with wet deposition velocity)	Contribute more to high values of chronic cancers in unstable weather (more dilution - less interdiction - wider spread - more cancers)
Power law parameters that define the standard deviation of the plume in the vertical (z) direction*	Dispersion	Important (not dominant) to both early and chronic consequences	Same as above	
Dry deposition velocity*	Deposition	Dominant to both early and chronic consequences	Surface roughness for meadow, city and forest aerosol particle size	
Linear term in washout model (exponential term should be assessed also)**	Deposition	Important (not dominant) to chronic consequences	Rain intensity, aerosol particle size	
Critical windspeed scale factor (plume rise only occurs if windspeed is less than critical windspeed—if speed is greater, plume is caught in wake)	Plume rise	Important (not dominant) for early consequences; dominant for safety goal fatality risk (dose at boundary)	Plume energy Windspeed Stability class Building scale length Ambient temperature	
Lethal dose (variable for bone marrow)	Health Effects	Important (not dominant) to early consequences	Specify period of exposure and period of manifestation	
Groundshine shielding factor for non-evacuees	Behavior of deposited material and calculation of related doses	Important (not dominant) to both early and chronic consequences	Experts must provide values for population in different types of shelters	

* The power law parameters that define plume spread are the a_y b_y a_z, b_z code input parameters discussed in Section 2.4.
** The linear and exponential terms in the washout model are the a_χ and b_χ wet deposition code input parameters discussed in Section 2.4.

Table 2.3 Code input variables for prompt and latent consequences (continued)

Important Code Input Variable	Proposed Expert Panel	Important to Early or Chronic Consequence Measures	Factors that Should be Considered in Elicitation Design	Comment
Inhalation protection factor for non-evacuees	Behavior of deposited material and calculation of related doses	Important (not dominant) to early consequences		
Dose/Dose Reduction factors (for 7 organs)	Late health effects	Important (not dominant) to chronic consequences		
Transfer factor food to beef - cesium (for cesium)	Food chain	Important (not dominant) to chronic consequences		The ingestion pathway models are different in MACCS and COSYMA—Consistency between MACCS and COSYMA could be a problem
Transfer factor to milk for I, Cs, Sr	Food chain	Did not show up as important in sensitivity calculation, but the interdiction criteria may have masked the effect of this variable		Consistency between MACCS and COSYMA could be a problem

experimentally observable parameters have the potential of containing uncertainty due to the fundamental limitations in model physics, data uncertainties, and random or stochastic uncertainties in observational data. Additional criteria used in the selection of elicitation variables and a summary of the elicitation variables chosen for the dispersion and deposition panel are provided in Section 3.2.

2.8 Selection of Formal Expert Judgment Methods

Expert judgement methods were identified by project staff as the best technology available for the development of uncertainty distributions for the selected consequence parameters. The two requisites for the application of formal expert judgment methods are (a) the experimental data base cannot provide the necessary information required by the project and (b) the analytical models that would provide information not observed experimentally are not indisputably correct. If these requisites are not met, expert judgment methods should not be used. It was determined by project staff that both of these conditions accurately describe the information currently available for selected consequence code input parameters.

The existing experimental data base for code input parameters is not adequate to support a comprehensive consequence uncertainty study. It is not complete in many relevant areas or is not directly applicable. Although there is much experimental information, it is somewhat controversial, often contradictory, and not always applicable to much of the area of interest in consequence analysis.

The models currently used to represent the complex processes involved in consequence analysis are generally quite rudimentary. No non-controversial, validated model exists that could be used to perform sensitivity studies that would adequately represent a comprehensive uncertainty study.

Table 2.4 Combined list of code input variables shown to be important

Phenomenological Area	Code Input Variable Requiring
Dispersion	Plume spread parameters*
Deposition	Dry Deposition velocity Wet deposition parameters*
Behavior of deposited material and calculation of related doses	Decontamination Resuspension parameters Weathering parameters Shielding factors Penetration factors
Plume rise	Amount of plume rise Critical windspeed for liftoff
Internal dosimetry	Breathing rate Dose conversion factors
Early health effects	Lethal dose thresholds
Late health effects	Dose rate effectiveness factors Risk coefficients (cancer)
Food chain	All food chain parameters

* The plume spread and the wet deposition parameters are the a_y b_y a_z b_z and the a_λ, b_λ code input parameters, respectively, discussed in Section 2.4.

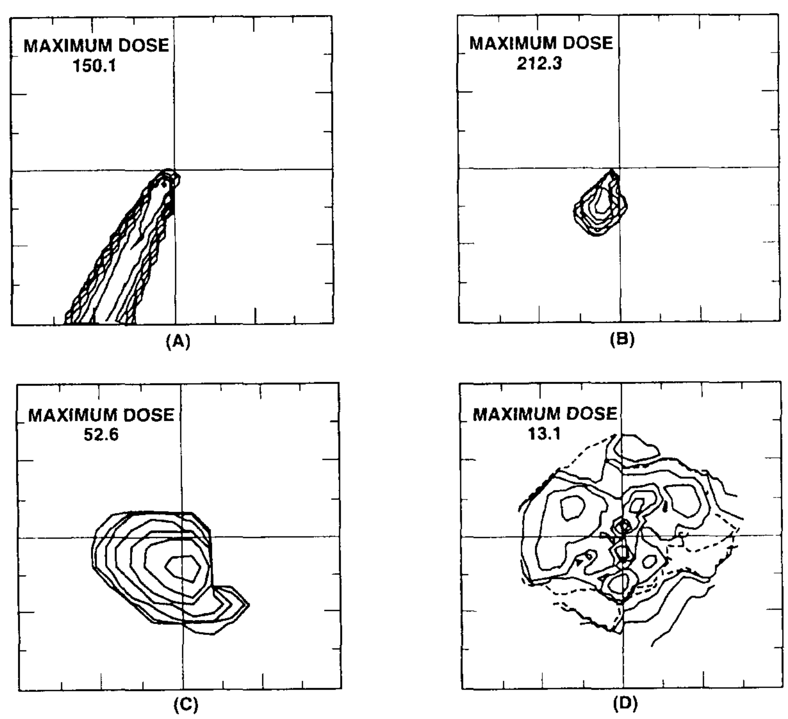

Figure 2.1 Predicted concentrations using various models compared to actual concentrations; one-hour surface doses predicted by (A) Gaussian plume model, (B) puff-trajectory model, (C) complex numerical model, and (D) doses actually observed

The validity of this argument is demonstrated in Figure 2.1, which shows the actual air concentration (plume) pattern observed for one of the tests performed in a 1981 study conducted at the Idaho National Engineering Laboratory in which a nonradioactive tracer (SF_6) was released. In Figure 2.1, the actual concentrations are compared with predictions made by various models to evaluate their potential use in emergency response situations. The models against which the measurements were compared are (a) a simple straight line Gaussian plume model, (b) a Gaussian-puff trajectory model, which accounts for wind shift, and (c) a more sophisticated wind field and topographic model used in the DOE's Atmospheric Release Advisory Capability (ARAC) program. Even the sophisticated ARAC model could not reproduce what actually occurred.

In addition to the deficiencies in the experimental data bases and the analytical models, expert judgment methods were chosen for this study for the following reasons:

(1) In order to develop uncertainty distribution over consequence parameters, it is necessary to filter and integrate large amounts of sometimes contradictory experimental and analytical results. There is no better group to perform this function than the people with the most expertise in the appropriate field.

(2) Differing viewpoints more completely capture uncertainty. The project does not require consensus from the experts, as required by some other formal expert judgment procedures (the Delphi technique). This is to preserve the uncertainty introduced by alternative modeling approaches.

(3) All processes, judgments, and rationales are made explicit and documented when using formal expert elicitation methods. In matters of importance, the traceability, credibility, and defensibility gained through these methods are necessary. Judgment is used in all analyses and models but is often not made explicit. This has caused much difficulty when results are interpreted and used.

2.9 Scope of Analysis

By the nature of the deposition and dispersion questions, it is impossible to develop distributions for deposition and dispersion variables that are valid for all nuclear power plants. The Gaussian dispersion model in MACCS and COSYMA is typically applied to dispersion scenarios over uncomplicated terrain, i.e., flat terrain or terrain with gently rolling hills. The project management therefore decided to elicit distributions only for dispersion over terrain that can be categorized as uncomplicated; surveys were performed in both the US and Germany to assess how many plants are located in such an area.[j,86] The results indicated that the majority of power plants are located in such areas.[k,87,l]

It was critical that the scope of the problems to be assessed was explicitly defined for the experts in order to receive consistent responses from the experts. During the expert meetings, guidelines were established for the phenomena to be considered in the definition of initial conditions for the distributions, the phenomena to be considered as part of the uncertainty, and the phenomena considered outside the scope of the project. Phenomena that were considered outside of the scope of the project were usually phenomena that are not addressed in MACCS and COSYMA. Lists of the phenomena included in the case structure, the phenomena not included in the case structure that should have been included in the uncertainty distributions, and the phenomena that were considered outside the scope of the project were developed by the staff and the experts jointly and are presented in Table 2.5 below.

[j] Sites classified as uncomplicated did not have significant terrain effects such as river valley channeling of wind or land/sea wind regimes; predominant stability classes were used to classify sites with marginally complicated terrain.

[k] March 16, 1993 letter from Mary Young, SNL to Christiana Lui, NRC.

[l] Helton, J.C., et al., Sandia National Laboratories, "Uncertainty and Sensitivity Analysis of Chronic Exposure Results with the MACCS Reactor Accident Consequence Model," NUREG/CR-6134, SAND93-2370, Albuquerque, NM, December, 1994.

Table 2.5 Phenomenological scope of uncertainty distributions

Type of Question	Uncertainty Resulting From These Phenomena Included In Distributions Provided By Experts	Uncertainty Resulting From These Phenomena Not Included In Distributions Provided By Experts
Dispersion	• meandering during sampling • mixing height • minor terrain variability • uncertainty in definition of synoptic weather conditions • directional wind shear • vertically changing turbulence (fumigation) • roughness height variability • wind profile • leaky inversion layers	• complex meteorology (for example time-dependent three-dimensional wind fields from convective processes or from complex orographical variations e.g., mountains)
Dry Deposition	• humidity • ambient and surface temperatures • variation in surface types • meteorological conditions except the wind-speed • chemical reactions with the surface of the aerosols • electrostatic effects • day and night differences	• vapor to particle conversion • resuspension
Wet Deposition	• electrostatic effects • vertical concentration profiles • rain intensity • hydrophobic/hydrophilic effects	• snow • mist/fog • rainout

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3. Summary of Methods for Atmospheric Dispersion and Deposition Panels

3.1 Introduction

The joint methodology used to develop uncertainty distributions to perform consequence calculations in this project is summarized in this section. A more detailed description of the joint methodology is presented in Volume III, Appendix D.

The methodology formulated for this project is a combination of methods from previous US and EC studies as well as methods developed specifically for the joint effort. Table 3.1 summarizes some of the major contributions to the joint methodology from previous US and EC studies.

Figure 3.1 is a graphical representation of the methodology applied in this project for the development of distributions over consequence code input parameters. The definition of goals and philosophies for uncertainty assessment, the prioritization of the consequence code input parameters, and the selection of the code input variables to be addressed were accomplished prior to the initiation of the atmospheric dispersion and deposition feasibility study and are discussed in Chapter 2 of this document. This chapter reviews the methodology applied in this project, specifically as it pertains to the development of distributions over atmospheric dispersion and deposition code input parameters.

3.2 Definition of Elicitation Variables and Case Structures

Elicitation variables are the variables presented to the experts for assessment. Experts were asked to provide distributions over variables within the context of a set of initial and boundary conditions. Each set of initial and boundary conditions for an individual question was termed a case. The ensemble of all cases for the elicitation variable is termed the case structure.

The primary consideration in the development of elicitation variables, cases, and case structures was the importance of designing elicitation questions that were not dependent on specific analytical models.

3.2.1 Definition of Elicitation Variables

It was the responsibility of the probability elicitation team to develop elicitation variables that were physically measurable parameters. The physically measurable constraint (as opposed to eliciting on a fitted exponent having no interpretation in terms of the physics of the problem) was imposed so that there will be no ambiguity when presenting the definition of the elicitation variables. If the experts assess poorly defined variables, the potential for incompatible assessments is high. Also, assessments on physically measurable parameters are not inherently dependent on any given theoretical model and therefore may be developed from a combination of relevant information sources.

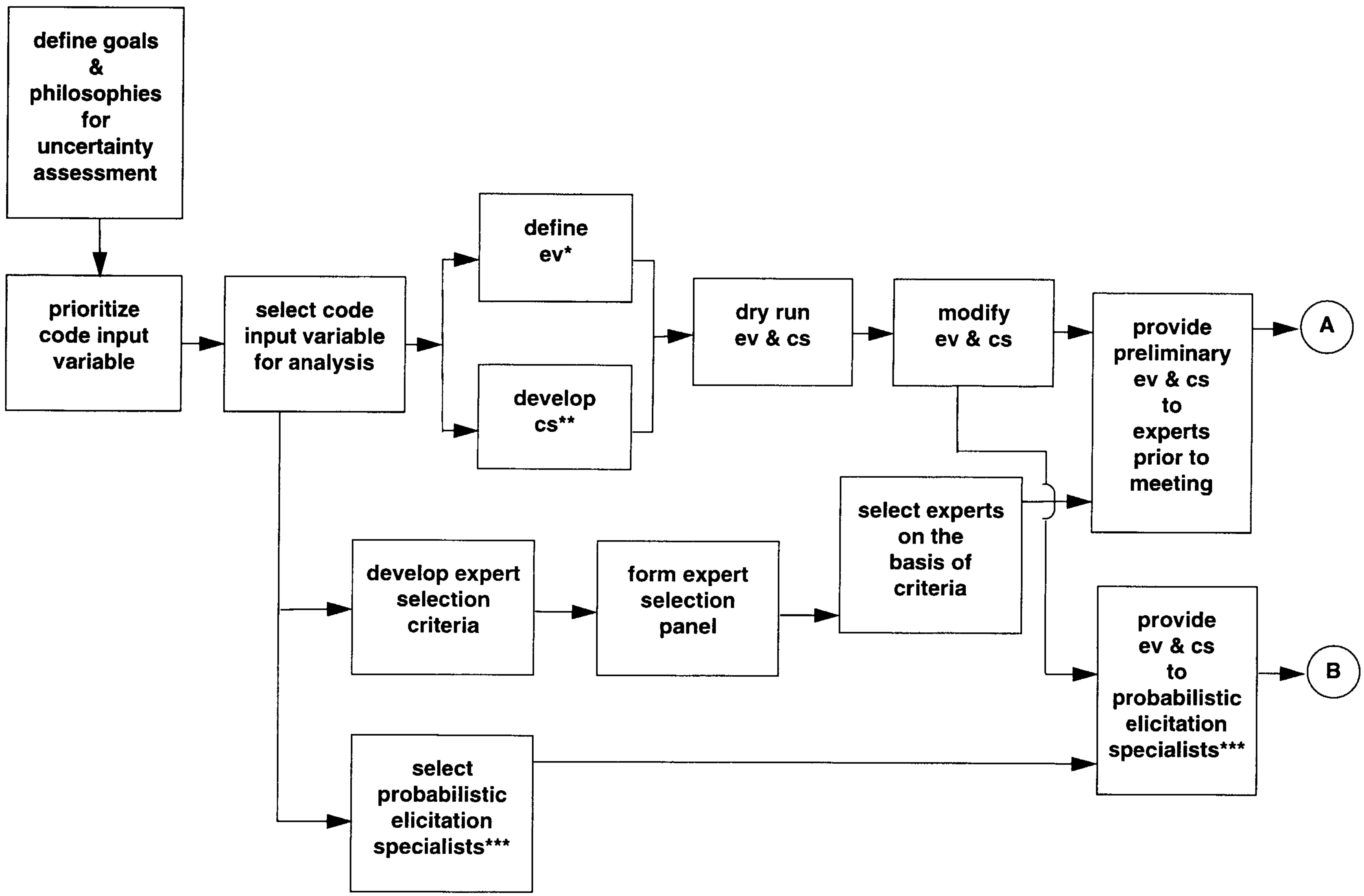
Code input parameters are not always physically measurable parameters. In the case of dispersion, the important code input parameters are mathematical constructs that define the spread of the plume in the Gaussian model. In the MACCS and COSYMA dispersion models, the horizontal spread (σ_y) and vertical spread (σ_z) parameters are modeled using the power law:

$$\sigma_y = a_y x^{b_y}; \sigma_z = a_z x^{b_z}$$

The code input parameters which define the spread of the plume are the a_y, b_y, a_z, b_z terms of the power law. They are

Table 3.1 Contributions to the joint methodology from US and EC studies

Contributions from previous US studies	Contributions from previous EC studies
Philosophy of choosing high quality experts and paying them	Ready made processing methodology and software for dispersion and deposition
Formal elicitation protocol developed for NUREG-1150	Concept of elicitation on variables that can be conceived as being experimentally observable
Probabilistic training and help in encoding probabilities during elicitation session for experts	Techniques for assessing performance of experts in encoding probabilities
Aggregation techniques using equal weighting for experts	



*ev = elicitation variables
**cs = case structures
***also called "normative specialists"

Figure 3-1 Sequence of methods used for the development of the uncertainty distributions

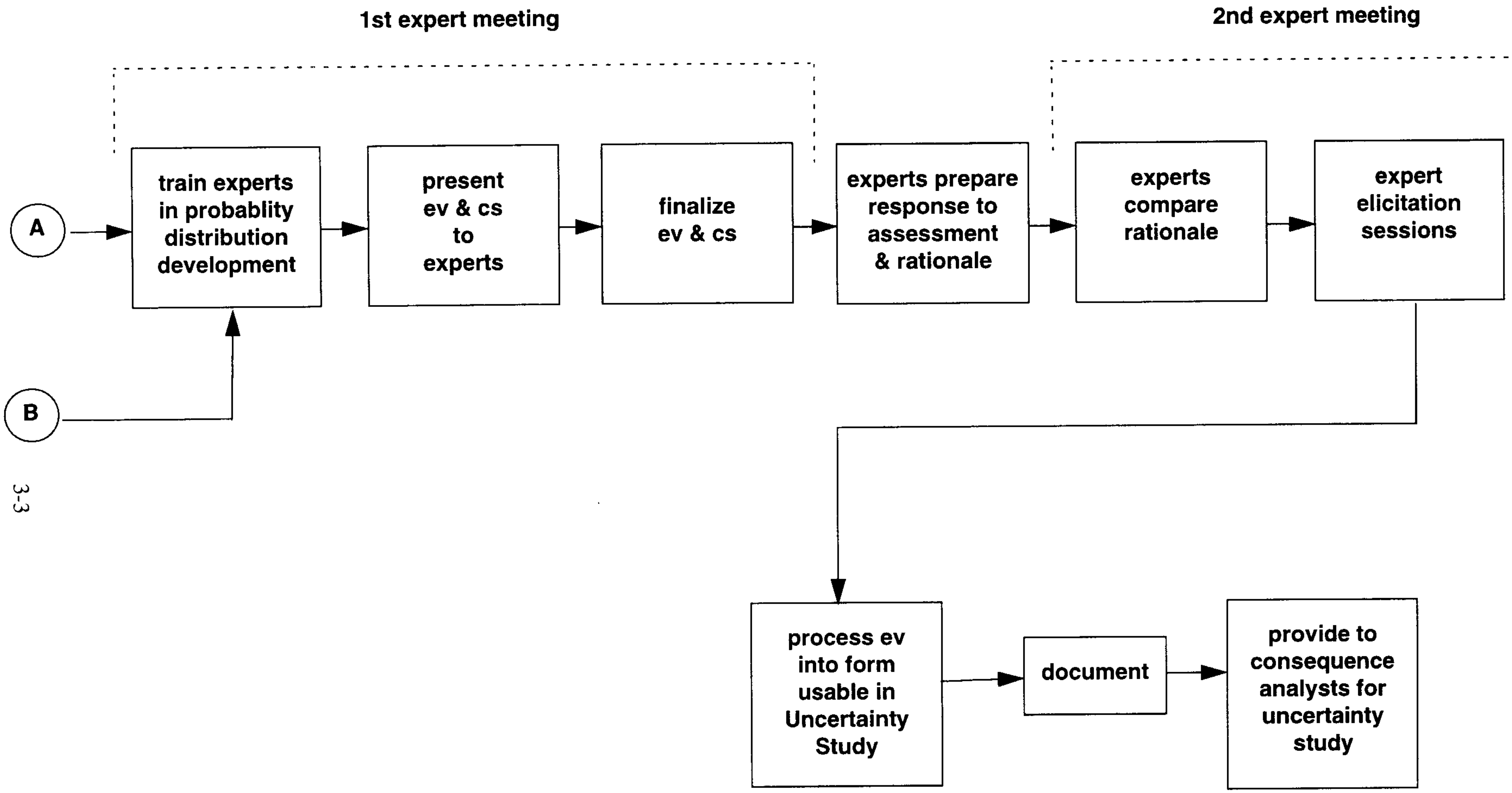


Figure 3-1 (continued) Sequence of methods used for the development of the uncertainty distributions

assigned values in MACCS and COSYMA depending on the atmospheric stability class. Because a_y, b_y, a_z, b_z are not physically measurable parameters, it was necessary to elicit distributions on physically measurable parameters from which could be derived distributions on a_y, b_y, a_z, b_z. The following elicitation variables were subsequently chosen for the dispersion case structures:

(A) The normalized concentration measured at a collector located at the centerline (χ_c/Q).

(B) The concentration relative to the centerline concentration at a specified crosswind location y (χ_y/χ_c).

(C) The concentration relative to the centerline concentration at a vertical distance, z and at the centerline, y=0 (χ_z/χ_c).

(D) The standard deviation associated with the cross wind concentration (s_y) as would be measured by a line of collectors at specified distance from the source.

(E) The total area [km^2] covered by 90% of the time-integrated concentration in the ring-shaped distance region between r_1 and r_2 (r_1 and r_2 are in the far field).

The elicited distributions obtained for the s_y and χ_c/Q parameters provide enough information to enable the development of distributions over the code input parameters using a mathematical processing method that was partially developed during the CEC pilot study. Project staff chose to elicit distributions for the χ_y/χ_c and χ_z/χ_c parameters so that distributions for a_y, b_y, a_z, b_z could also be developed using an alternative, more general mathematical processing methodology.

The code input parameter for dry deposition is the dry deposition velocity, v_d, which is defined as the ratio of the rate of deposition of radioactivity to the ground to the air concentration at ground level. The dry deposition velocity is a physically measurable parameter and was therefore chosen as the elicitation variable for the dry deposition questions. Distributions were elicited on the dry deposition velocity for four surface types, aerosols of six particle sizes, elemental iodine, and methyl iodide.

As with dispersion, the important code input parameters for wet deposition are mathematical constructs, not physically measurable parameters. The important code input parameters for wet deposition are those that define the removal coefficient for wet deposition, which may be written as:

$$\Lambda(I) = a_\lambda I^{b_\lambda} .$$

where I is the rain intensity. The code input parameters for wet deposition are the a_λ and b_λ terms in the above equation. It was therefore necessary to define a physically measurable elicitation variable from which could be developed uncertainty distributions for a_λ and b_λ. The fraction of material removed by wet deposition was chosen as the elicitation variable for wet deposition. Uncertainty distributions were elicited for the fraction of material removed by wet deposition for aerosols (four particle sizes), elemental iodine, and methyl iodide.

In addition to questions relating to the elicitation variables, questions were presented to the experts for which experimental answers were known. These variables, known as seed variables, are used to measure performance in encoding scientific belief into probabilistic distributions. These questions were used to provide feedback during the probabilistic training exercise and to form the basis for measuring performance of the elicitation variables.

3.2.2 Development of Case Structures

It was impossible for the experts to provide information over the complete variable space needed to perform a comprehensive consequence uncertainty study. It was therefore necessary to design a case structure that would cover the variable space so that the project could interpolate and extrapolate to all areas necessary to perform consequence uncertainty studies.

For the dispersion questions, the case structure consisted of many permutations of downwind distances and the synoptic weather conditions at the source. For the deposition questions, the case structure consisted of many permutations of different surface types, particle sizes, chemical types, rain intensities (for wet deposition), and rain duration (for wet deposition).

The initial iteration of the case structure design for dispersion and deposition resulted in a very large number of cases (in principle an infinite number of situations can be described): 700 dispersion cases, 150 dry deposition cases, and 40 wet deposition cases. It would be impossible to expect the experts to provide distributions for this enormous number of cases. After several iterations, a condensed version of the case structure evolved and was tested in dry run elicitations. The dry run elicitation was performed using two dispersion experts and one deposition expert from Sandia National Laboratories (SNL). After the final iteration on the case structure, the dispersion experts were asked to assess 101 questions. The deposition experts were asked to assess 106 questions (70 on dry deposition and 36 on wet deposition). The project staff believed that sufficient information would be obtained from these questions to allow valid interpolation and extrapolation for coverage of the variable space.

3.2.2.1 Case Structure for Dispersion Questions

For each elicitation variable, experts were asked to provide three percentile values, 5th, 50th, and 95th, from the cumulative distribution functions, with assessments of the absolute upper and lower bounds optional. These distributions were elicited for various specified atmospheric conditions (case structures). Each of the variables elicited can be explained in terms of realizations from a single event.

The variables were elicited for various meteorological conditions at the plume axis height, h. The wind direction is defined as the x-direction. The crosswind direction, y, is perpendicular to the plume centerline direction and parallel to the grade. The vertical height above ground is z. The plume centerline direction is defined as the average transport direction of the plume. The sampling time for each designated downwind, crosswind, and vertical distance is specified. The sampling time is designated as one hour. Exceptions to the one-hour sampling time were made in a few cases for the seed variables. The release duration of the plume was equal to or exceeded the sampling time in all cases.

Table 3.2 shows the four generic meteorological conditions that were assessed by the experts. The meteorological conditions prior to the event and during the entire event are constant for elicitation purposes. Conditions were specified at the release point which is $x_0 = 0$, $y_0 = 0$ and $z_0 = 10$ m. Table 3.3 shows the downwind distance sampling locations for the four example meteorological cases.

Several initial conditions were not specified. The experts were instructed to include any unspecified effects in their uncertainty distributions. For example, the terrain surrounding the release site is specified as simple terrain; however, the uncertainty distribution should include the effects of both flat terrain and gently rolling hills. The experts were instructed not to include the effects of complex terrain. Crosswind broadening of the concentration distribution

Table 3.2 Example case structure

Meteorological Condition	Temperature Lapse Rate	Standard Deviation of wind direction at 10 m averaged over 10 min (σ_θ)	Average Wind Speed	Surface Roughness
1	-2.0 K/100 m	25°	2 m/s	combination of urban and rural
2	-1.6 K/100 m	15°	4 m/s	combination of urban and rural
3	-1.0 K/100 m	10°	6 m/s	combination of urban and rural
4	2.5 K/100 m	2.5°	3 m/s	combination of urban and rural

Table 3.3 Sampling locations for case structure

Downwind Distance x (km)	Crosswind Distance y (km)	
	Met. Condition 1	Met. Condition 2
0.5	0.17	0.10
1.0	0.30	0.20
3.0	0.85	0.50
10.0	2.5	1.5
30.0	6.7	4.0

because of plume meander during the sampling time is another uncertainty that should be included, as well as anything else the expert considered important to include in the uncertainty distribution. Additionally, all experts were asked to specify any assumptions regarding mixing layer height made during their elicitations.

Data were also elicited to assess uncertainty in long term dispersion. A few questions in the following form were asked:

> What are the 0th, 5th, 50th, 95th, and 100th percentile values for the length of the arc or sum of the arcs crossed by 90% of the material at 80 km, 200 km, and 1000 km downwind of the release?

The information elicited for long term dispersion was acquired only for the purpose of developing uncertainty distributions for long term dispersion data. The long term dispersion data will be processed by the consequence analysts performing the uncertainty study. This information was not processed beyond the elicitation exercise in this study.

3.2.2.2 Case Structure for Dry Deposition Questions

Four surface types were considered in the case structures: (1) urban, (2) meadow, (3) forest, and (4) human skin. The urban surface type consists of buildings and concrete. The meadow surface type includes bare soil, freshly cut grass, pasture, and crops such as harvestable corn. The forest surface type includes any kind of tree, including deciduous and evergreen varieties. Human skin refers to skin that would be exposed to a passing plume.

The particulate forms for which data were elicited were: aerosol, elemental iodine, and methyl iodide (for the purposes of the elicitation, iodine is assumed not to deposit on aerosols). The sampled particle sizes for the aerosol cases were specified within the following series: 0.1 μ, 0.3 μ, 1.0 μ, 3.0 μ, and 10.0 μ. Particle sizes are associated to spherical particles of unit density (1 gram/cm^3).

The only initial condition specified for dry deposition was the average wind speed. The experts were instructed to include any effects not specified in their uncertainty distributions. For example, humidity, ambient air temperature, chemical reactions, other meteorological conditions, vapor-to-particle conversion, and variations within surface type were considered as unknowns, as well as any other effects the expert considered important.

3.2.2.3 Case Structure for Wet Deposition Questions

The elicitation variable for wet deposition, the fraction of material removed from the plume, is the total fraction removed during the entire time period specified. The rain intensity was specified in two ways in the case structure: (1) the average rain intensity during 1 hour in which it does not necessarily rain continuously during the hour, and (2) the rain intensity during 10 minutes in which it rains continuously during the 10-minute period.

The particulate forms elicited were aerosol, elemental iodine, and methyl iodide. The sampled particle sizes for the aerosol cases were specified within the following series: 0.1 μ, 0.3 μ, 1.0 μ, and 10.0 μ; particle sizes are associated with spherical particles of unit density (1 gram/cm^3).

The average rain intensities for the one hour cases were defined as the following amounts of precipitation recorded over one hour:

> 0.3 mm, including drizzle, rain and showers;
> 2.0 mm, including rain and showers.

The average rain intensities for the ten minute cases were defined as the following amounts of precipitation recorded over ten minutes:

> 0.05 mm, drizzle;
> 0.33 mm, rain;
> 1.67 mm, a shower.

Several initial conditions were not specified. The experts were instructed to include any effects not specified in their uncertainty distributions. For example, chemical reactions, electrostatic effects, vertical profiles and rain rate are considered as unknowns, as well as any other effects the expert considers important. The rain is assumed to be consistent over the entire area.

3.3 Expertise Required for the Elicitation Process

The design for the probability elicitation sessions in this study was taken from the methodology developed for the NUREG-1150 study. This design includes an elicitation team composed of the phenomenological experts whose judgments are sought, a normative specialist who manages the session, and a substantive assistant from the project staff who aids communication between the expert and the specialist and helps answer questions about the assumptions and conditions of the study.

The normative specialist is an expert in probability elicitation. The role of the normative specialist is to ensure that the expert's knowledge is properly encoded into probability distributions. To accomplish this aim, the specialist must be alert to the potential for biases in judgment formation. The specialist also tests the consistency of judgments by asking questions from various points of view and checking agreement among the various answers. Another role is ensuring that the expert expresses rationales for the judgments and is able to substantiate any assumptions that are made. Along with the phenomenological expert, the normative specialist ensures that the distributions are properly recorded and annotated to curtail ambiguity in their meanings.

The substantive assistant brings knowledge of project assumptions and conditions to the study. The role of this participant is to promote a common understanding of the issues and to clarify and articulate how the data will be interpreted in the modeling activities. This team member also has responsibility for assisting the expert with documentation of rationales.

3.3.1 Selection of Phenomenological Experts

The project staff sought to engage the best experts available in the fields of atmospheric dispersion and deposition. Experience in the NUREG-1150 study and elsewhere has shown that the selection of experts can be subjected to much scrutiny. Thus, it was necessary to construct a defensible selection procedure. The selection procedure for this study involved the following: (1) a large list of experts was compiled from the literature and by requesting nominations from organizations familiar with the areas; (2) the experts were contacted and curriculum vitae (CV) were requested; (3) two external committees, one in the US and one in the EC, were established and charged with expert selection based on a common set of selection criteria, which included reputation in the relevant fields, number and quality of publications, familiarity with the uncertainty concepts, diversity in background, balance of viewpoints, interest in this project, and availability to undertake the task in the time–scale prescribed. The result was two panels of internationally recognized scientists, half of whom were from the US and half of whom were from the EC. Table 3.4 lists the experts who participated in this study. Brief biographies of the individual experts are provided in Volume II.

3.3.2 Selection of Normative Specialists

Normative specialists have the responsibility of managing the elicitation sessions. These specialists come from various fields such as psychology, decision analysis, statistics, or risk and safety analysis. The characteristic that distinguishes these specialists is a cognizance of the methods and literature for probability elicitation and experience in applying these methods. Normative specialists must be able to manage the elicitation sessions by providing assistance in developing and expressing quantitative judgments.

Four normative specialists were used in this study. Three of these specialists (Dr. Goossens, Dr. Hora, and Mr. Kraan) were part of the project staff. They were supplemented by an additional specialist, Dr. Detlof von Winterfeldt. Drs. Goossens and Hora have extensive experience in probability elicitation. Dr. Goossens has managed a number of studies involving expert judgment for the safety institute at TU Delft and is familiar with the areas of dispersion and deposi-

Table 3.4 Atmospheric dispersion and deposition experts

Dispersion Experts	Country	Deposition Experts	Country
Pietro Cagnetti	Italy	John Brockmann	U.S.A.
Frank Gifford	U.S.A.	Sheldon Friedlander	U.S.A.
Paul Gudiksen	U.S.A.	John Garland	U.K.
Steve Hanna	U.S.A.	Jozef Pacyna	Norway
Jan Kretzschmar	Belgium	Joern Roed	Denmark
Klaus Nester	Germany	Richard Scorer	U.K.
Shankar Rao	U.S.A.	George Sehmel	U.S.A.
Han van Dop	Netherlands	Sean Twomey	U.S.A.

tion. Dr. Hora joined the project team for the specific purpose of bringing probability elicitation expertise to the project. He was a key participant in the NUREG-1150 expert elicitation activities.

Mr. Bernd Kraan of TU Delft is experienced in the processing of expert judgments. Dr. von Winterfeldt is internationally known in the field of decision analysis and has served as a consultant on many projects involving expert judgment elicitation. He also participated in the NUREG-1150 study.

3.4 Expert Elicitation

The expert elicitation process consisted of the following activities:

(1) Dry run elicitation:
A dry run elicitation was conducted with dispersion and deposition experts recruited from SNL. The purpose of the dry run was to test the methodologies to be used in the actual expert elicitation meetings and to evaluate the case structures.

(2) First expert meeting:
The purpose of the first expert meeting was to train the experts in providing their judgments in terms of probability distributions and to present the technical problems to be assessed.

(3) Expert prepares assessment:
The expert prepared his assessment of the problems posed in the first meeting. The expert also prepared to provide the staff with the rationale behind his distributions in written form before leaving the second meeting. No requirements on the form of the written rationale were imposed.

(4) Second expert meeting:
The second expert meeting was conducted approximately six weeks after the first expert meeting. The purpose of the second meeting was to elicit from the experts the percentile values from the cumulative distributions of the elicitation variables.

3.4.1 Dry Run Elicitation

The dry-run meeting was conducted in March 1993 with dispersion and deposition experts from SNL. Dr. Bernard Zak and Dr. Hugh Church served as the dispersion experts. Dr. John Brockmann served as the deposition expert. The meeting began with training in probability elicitation. The training focused on the meaning of subjective probabilities, the structure of formal expert judgment processes, biases in probability formation, and practice in expressing judgments as probabilities. The training ended with a training quiz in which the SNL experts were given questions in their fields with known answers: the actual value for the experiment was then compared to the distributions provided by the SNL experts. Feedback on probabilistic distribution development was then provided to the SNL experts prior to the elicitation session.

During the actual expert elicitation for this project, the experts were given approximately six weeks to prepare their response for the final elicitation. The dry run experts were given the elicitation questions and were required to prepare their response on the same day (the day of the dry run), although they were allowed to prepare their response prior to the elicitation session.

Suggestions were solicited from the dry-run experts about the usefulness of the training in probability elicitation and the appropriateness of the training variables. The case structures to be presented to the experts in the first meeting were finalized according to the lessons learned in the dry run.

3.4.2 First Expert Meeting

Prior to the first meeting, a brief description of the process and the elicitation questions were provided to the experts. Reading this description was the only preparation necessary for the first expert meeting.

In the first expert meeting, the experts were introduced to the purposes of the study, including how their judgments were to be used. The case structures, a clear definition of the variables to be assessed, and a description of how the information provided by the expert would eventually be used by the project staff was provided. The experts were also introduced to background material on consequence codes and the science of probability elicitation. This required the distribution of materials explaining the consequence area, the relation of the questions posed to the parameters in the model, and the specific initial conditions and assumptions to be used in answering the elicitation questions. Training was conducted to introduce the experts to the psychological biases in judgment formation and to give them feedback on their performance in assessing probability distributions.

In the NUREG-1150 study, feedback was provided to the experts by measuring their performance on the development of probabilistic distributions for training variables. The training variables were non-technical almanac type questions for which the answers were known. In the current study, performance is measured by querying the experts about variables whose true values are uncertain for the experts but known to project staff from actual experiments. These seed variables were chosen to resemble the variables of interest as closely as possible.

3.4.3 Preparation of the Distributions

Following the first meeting, the experts spent one to two weeks preparing responses to the elicitation questions and preparing a statement explaining their information sources and rationale. The experts were encouraged by project staff to use whatever modeling technique or experimental results they felt appropriate to assess the problems. The only constraints placed on the experts by the project were: (1) the initial conditions had to be defined at the same level of detail as the code input (uncertainty due to lack of detail in the initial conditions had to be included in the uncertainty distributions provided) and (2) the rationale behind the distributions had to be thoroughly documented.

3.4.4 Second Expert Meeting: Elicitation

On the first day of the elicitation meeting, a common session was conducted where the experts presented the technical approach and rationale behind their assessments. No distributions were provided in the common sessions to avoid biasing the other experts. The elicitation of each expert took place privately with a normative specialist and a substantive assistant. The experts were allowed to change their elicitation results at any point. The elicitation interviews allowed for significant interaction between the assessment team and the expert in the encoding of probabilities. At the end of the elicitation session, a questionnaire was distributed to the experts to obtain formal feedback on the process.

3.5 Mathematical Processing of Elicited Distributions

At the end of the elicitation sessions, the project staff had, from each expert, the 5th, 50th, and 95th percentile values from the cumulative distribution of each elicited variable for each case structure. It was the responsibility of the project staff to aggregate the individual expert distributions (5th, 50th, and 95th percentile values) for each elicitation variable for each case structure into a single cumulative distribution for each elicitation variable for each case structure.

No further mathematical processing was required for the aggregated dry deposition data because the dry deposition elicitation variable was the important code input variable for the dry deposition model in the consequence codes.

The dispersion and wet deposition elicitation variables were not the consequence code input parameters for dispersion and deposition. Further mathematical processing of these results was necessary in order to obtain distributions over the important code input parameters.

This section briefly reviews the mathematical processing of the elicited distributions.

3.5.1 Aggregation of Elicited Distributions

The processing tool for combining expert assessments is the computer code EXCALIBR[1]. Inputs for EXCALIBR are percentile assessments from experts for query variables, both elicitation variables and seed variables. A cumulative distribution function (CDF) is associated with the assessments of each expert for each query variable in such a way that (1) the cumulative probabilities agree with the expert's percentile assessments, and (2) the cumulative probabilities are minimally informative with respect to the background measure, given the percentile constraints. The background measures are either uniform or loguniform, depending on the width of the uncertainty band for the variable as elicited from the experts. For each variable, non-negative weights summing to one are assigned to the CDFs developed for the individual expert assessments, and the aggregation is accomplished by taking the weighted sums of the cumulative probabilities for each variable. EXCALIBR outputs the 5th, 50th, and 95th percentiles and percentiles from the combined CDF for each variable.

EXCALIBR contains three different weighting schemes for aggregating the distributions elicited from the experts. These weighting schemes are equal weighting, global weighting, and item weighting. The different weighting schemes are distinguished by the method the weights are assigned to the CDFs of each expert. The equal weighting aggregation scheme assigns equal weight to each expert. If N experts have assessed a given set of variables, the weights for each density are 1/N; hence for variable i in this set the decision maker's CDF is given by:

$$F_{ewdm,i} = (1/N)\sum_{J=1}^{N} f_{j,i}$$

where $f_{j,i}$ is the cumulative probability associated with expert *j*'s assessment for variable *i*.

Global and item based weighting techniques are termed performance based weighting techniques because weights are developed based on an expert's performance on seed variables. Global weights are determined, per expert, by the expert's calibration score and overall information score. The calibration score is determined per expert by his assessments of seed variables.[a] The information score is a function of the width of the uncertainty band provided by the expert. As with global weights, item weights are determined by the expert's calibration score. Whereas global weights are determined per expert, item weights are determined per expert *and* per variable in a way that is sensitive to the expert's informativeness for each variable. Additional information regarding performance-based weighting techniques can be found in Volume III, Appendix D.

Investigating the different weighting schemes was not the objective of this joint effort. A programmatic decision was therefore made to assign all experts equal weight, i.e., all experts on each respective panel were treated as being equally credible. One of the primary reasons the equal weighting aggregation method was chosen for this study was to insure the inclusion of different modeling perspectives in the aggregated uncertainty distributions. However, additional information was elicited from the experts to allow the application of performance based weighting schemes to the elicited distributions.

3.5.2 Mathematical Processing of Wet Deposition and Dispersion Aggregated Distributions

Prior to this study, a method was developed under CEC sponsorship which was capable of developing, from the aggregated elicited deposition distributions, distributions over the wet deposition code input parameters (a_λ,b_λ). The PARFUM[2] software package was developed for the implementation of this methodology. Under the sponsorship of the present study, the capabilities of the PARFUM methodology were expanded to be able to develop, from the aggregated elicited dispersion distributions, distributions over the consequence code dispersion input parameters (a_y, b_y, a_z, b_z). The expanded PARFUM methodology developed to process the aggregated elicited dispersion distributions is referred to in this study as the Sigma processing methodology, which is an under-constrained optimization method based on the Gaussian plume model (GPM). It utilizes only the aggregated elicited distributions for s_y and χ_c/Q; s_y is equated to the σ_y of the GPM, and distributions for the dispersion code input parameters are developed using the GPM implemented in the consequence codes. The uncertainty in cross-wind plume growth and χ_c/Q are captured by the Sigma methodology.

The Chi processing methodology was developed for this project as a more general approach designed to capture the uncertainty in the plume profile as well as the uncertainty in cross-wind plume growth and χ_c/Q. The Chi processing methodology is an over-constrained optimization method which utilizes the aggregated elicited distributions for χ_c/Q, χ_y/χ_c, χ_z/χ_c. Unlike the Sigma processing methodology, the Chi processing methodology is not inherently based on the GPM. However, because of project constraints against the modification of the code GPM, it was necessary to use the code GPM with the Chi methodology for the transformation of the elicited aggregated distributions into distributions over the code input variables.

A more detailed discussion of the PARFUM, Sigma, and Chi processing methodologies is presented in Volume III, Appendix E.

3.5.3 Evaluation of Mathematical Processing Methodologies for Wet Deposition and Dispersion

The robustness of the mathematical processing methodologies for wet deposition and dispersion were evaluated using the following approach:

(1) Uncertainty distributions over the wet deposition code input parameters were developed using PARFUM methodology.

(2) Uncertainty distributions over the dispersion code input parameters were developed using the Sigma and Chi processing methodologies.

(3) The uncertainty distributions over the dispersion and wet deposition code input parameters were used with

[a] The true values of the seed variables are known to project staff from recently obtained, unpublished experimental data. The true values of the seed variables are not known to the experts.

the dispersion and wet deposition models in the consequence codes to reformulate the distributions over the elicited parameters.

(4) The reformulated distributions over the elicited parameters were compared to the actual aggregated elicited distributions.

(5) The processing methodology was considered to be successful if the aggregated elicited distributions were accurately duplicated using the uncertainty distributions over the code input parameters.

3.6 References

1. Cooke, R., and D. Solomatine, Delft University of Technology and SoLogic Delft, "EXCALIBR, Integrated System for Processing Expert Judgments, Version 3.0: User's Manual," Delft, The Netherlands, 1992.

2. Cooke, R.M., and F. Vogt, Delft University of Technology, "PARFUM Parameter Fitting for Uncertain Models: Concepts and Code for Accident Consequence Modeling," Delft, The Netherlands, February 1993.

3. Summary of Methods for Atmospheric Dispersion and Deposition Panels

4. Results and Analysis

4.1 Introduction

This chapter reviews the responses of the experts to the elicitation meetings, the elicited data, the aggregated elicited distributions, and the final distributions developed for the dispersion and deposition code input parameters.

4.2 Summary of Elicitation Meetings

As discussed in Chapter 3 of this document, three meetings were conducted relating to the actual elicitation exercise. This section reviews the responses of the experts to the project materials and the methods presented during the elicitation meetings.

4.2.1 Dry Run Elicitation Meeting

The robustness of the basic expert elicitation methodology developed for this project was validated by the dry run exercise; however, several important issues were raised and subsequently evaluated as a result of the dry run. The issues raised were: (1) the wind speed was considered important to dry deposition and was added as part of the dry deposition case structure; (2) it was pointed out that the project could consider detail beyond the detail in the codes in the uncertainty study by using correlation of variables (for example, the wind speed in the dry deposition velocity model); (3) the possibility was considered of including the effects of electrical charge on aerosol behavior in the case structure and was discarded as a secondary influence (these effects were, however, included as part of the uncertainty in the elicited distributions); and (4) the dispersion case structure appeared to be appropriate for the elicitation of data to be processed through the Gaussian plume model (GPM) as all of the data provided by the dry run dispersion experts were consistent with the GPM.

The dry run experts reported that the probability training sessions were helpful in terms of improving their ability to encode their knowledge and judgment into probability distributions. The experts indicated that the training variables were well chosen in that they were directly relevant to the elicitation variables over which distributions were to be elicited. The dry run experts expressed a preference for individual elicitation sessions. They believed the individual elicitation sessions were more effective than group elicitation sessions for eliciting individual expert judgments because group elicitation sessions can be dominated by strong personalities who may unduly influence the judgment of others.

4.2.2 Summary of First Expert Meeting

The agenda from the first expert meeting is presented in Volume III, Appendix C. The initial reception of the project by the experts was excellent. The experts expressed a deep interest in the prospect of addressing uncertainty in their field of expertise.

After the probabilistic training exercise, the elicitation variables and the case structure were discussed. Several changes to the definition of the elicitation variables and the case structure were proposed in both dispersion and deposition questions, but as the experts became more familiar with the problem, the original definitions of the elicitation variables were found to be satisfactory.

The dispersion experts were comfortable with the use of the Gaussian models in the MACCS and COSYMA codes for the conditions within which the models will be applied in uncertainty studies. Although the deposition experts had little problem with the deposition questions and the case structure, they questioned the use of the source depletion model in the MACCS and COSYMA codes and the omission of the rainout phenomenon. They provided some constructive and relatively inexpensive solutions to address some problems they observed in the consequence codes.

For historical records, the entire meeting was videotaped.

4.2.3 Summary of Second Expert Meeting

The first day of the second expert meeting consisted of presentations by the experts on their approaches to the assigned problem. The approaches were given, but the actual probability assessments were not revealed, in order to avoid biasing other experts. At the end of the first day, the issue of anonymity was discussed. The experts decided to keep the elicitation results and the written rationales anonymous. The names of the experts will be published, and the work that the experts performed for this study will be published, but the experts' names will not be associated with their specific work.

The remainder of the second expert meeting consisted of individual expert elicitation sessions. The initial common session was videotaped, and the individual sessions were audiotaped.

At the end of the session, the experts were asked to fill out a form indicating the difficulties that were encountered during their involvement with the project, the areas in the project that could be clarified or improved, the areas that were currently acceptable, and their general feelings toward the project. The experts were unanimously favorable toward the project. Most experts indicated they had no problem whatsoever with any aspects of the project, but a few indicated difficulties with the description of the case structure and difficulties encoding their scientific judgment into probability distributions.

The experts were also asked whether the formal expert elicitation approach taken by the project was a reasonable approach for assessing uncertainties in the dispersion and deposition fields. They generally felt that the use of formal expert elicitation was an effective and appropriate method for capturing the uncertainty in their respective fields.

4.3 Summary of Individual Expert Assessments

Representative results are summarized and discussed in this section. Because a large number of figures are included in this chapter, they are presented at the end of the chapter so as not to interrupt the flow of the text.

The complete set of expert rationales and the elicited distributions are published in Volume II, Appendix A of this report. In this chapter, Figures 4.1 through 4.18 plot some of the elicited results along with the results of the equal weighted aggregation of the elicited distributions. The figures designate deposition experts 1 through 8 and dispersion experts 1 through 8. Appendix A designates experts A through P; there is no correlation between the two systems of designated experts. This section discusses only the individual assessments, Section 4.4 reviews the results of the equal aggregation of the distributions.

4.3.1 Summary of Individual Dispersion Assessments

Several dispersion experts relied on GPMs as the central basis for their elicitations, but they relied on non-Gaussian considerations to develop the requested information on the broader uncertainty distribution. Figures 4.1 and 4.2 show the elicited median values for the centerline concentration ratio for Stability Class A (Figure 4.1) and for Stability Class E/F (Figure 4.2). As can be seen, there was more variability among experts for the stable case (Figure 4.2) than for the non-stable case (Figure 4.1). However, the width of the uncertainty distributions (95th/5th percentile ratios) provided by the experts for the two cases look very similar, as shown in Figures 4.3 and 4.4.

The same trend is observed for the elicited crosswind dispersion assessments (s_y) in Figures 4.5, 4.6, 4.7, and 4.8. There is more variability in the stable median values than in the non-stable median values, but the variability in the width of the uncertainty distributions for the two cases is about the same. The experts seem to agree more closely in their median assessments for the near field, but diverge somewhat as the plume moves downwind. There is more variability among the experts in the widths of the s_y uncertainty distributions, as reflected in the 95th/5th percentile ratios, than in the median assessments.

4.3.2 Summary of Individual Dry Deposition Velocity Assessments

The variability among responses was greater for the dry deposition questions than for the dispersion questions. Generally, the deposition experts relied heavily on experimental evidence and used several analytical models to fill the gaps left by the experimental evidence. Figures 4.9 through 4.12 are examples of the variability observed among deposition experts for the dry deposition velocities of five different size aerosols on urban surfaces (Figures 4.9 and 4.10) and the dry deposition velocities of elemental iodine on forest, meadow, urban, and skin surfaces (Figures 4.11 and 4.12). In Figures 4.9 and 4.11 the 50th percentiles are shown as a representation of the central measure of the uncertainty distribution. In Figures 4.10 and 4.12 the 95th/5th percentile ratios are shown to represent the width of the elicited uncertainty ranges.

Figure 4.9 shows that most experts, except for the 10 μm particle size, established relatively low medians for aerosol deposition velocities. Expert 2, however, placed his median deposition velocity much higher. Figure 4.10 shows some order of magnitude differences between the width of the uncertainty distributions assessed by the experts. In Figure 4.11 the highest variability for the dry deposition velocities of elemental iodine is for deposition onto skin. Deposition on skin is not usually considered by deposition experts, and there is an absence of measurements of deposition to skin for the aerosols of interest. Figure 4.12 shows order of magnitude differences in the width of the uncertainty distributions provided by the experts for the dry deposition velocity of elemental iodine.

4.3.3 Summary of Individual Wet Deposition Assessments

As with the dry deposition responses, the variability among the wet deposition responses was greater than for the dispersion responses. Figures 4.13 through 4.16 are examples of the variability observed among the wet deposition experts for the fraction of aerosols of four different particle sizes removed by rainfall of .33 mm during 10 minutes (Figures 4.13 and 4.14) and the fraction of elemental iodine removed by rain during a 10 minute period for various rain intensities (Figures 4.15 and 4.16). Expert 2 did not assess the wet deposition questions and is therefore not included in the figures. Figures 4.13 and 4.14 show order of magnitude differences among the experts in both the median assessments and the width of the uncertainty distribution for the fraction of aerosols removed by rainfall. Figure 4.15 shows less than an order of magnitude variability among experts in the fraction of elemental iodine removed, except for Expert 1. Figure 4.16 shows less than an order of magnitude variability in the width of the uncertainty distributions, with the exception of Expert 4.

4.4 Summary of Aggregated Results

This section presents the results of the equal weighted aggregation of the individual elicited distributions into single distributions over each elicited parameter. Distributions were also developed using performance based weighting techniques, and these results are presented in Volume III, Appendix D.

4.4.1 Summary of Aggregated Dispersion Assessments

The 50th percentile and 95th/5th percentile ratios for the equal weighted aggregated distributions are presented along with the individual assessments in Figures 4.1 through 4.8. The 50th percentiles from the aggregated distributions appear consistent with the individual assessments. The plots for the 95th/5th ratios show that aggregation of the distributions may result in aggregated distributions which have a wider uncertainty band than any of the individual elicited distributions. Figures 4.17 and 4.18 are individual plots of the 5th and 95th ratios for the s_y elicited variable which show that, when plotted independently, the aggregated results for the 5th and 95th quantiles appear consistent with the aggregated distributions.

To give the reader the perception of what the uncertainty presented by the experts would look like when applied to a plume, the uncertainty in crosswind dispersion (s_y) is plotted in Figures 4.19 and 4.20 for stability classes F and A respectively. The figures represent the potential uncertainty in crosswind plume growth, which is substantial.

4.4.2 Summary of Aggregated Dry Deposition Velocity Assessments

Figures 4.9 through 4.12 plot the central measure and the uncertainty measure of the aggregated distributions for aerosols and elemental iodine dry deposition velocities. The 50th percentile aggregated values appear to be consistent with the individual elicited distributions. As with the dispersion results, the ratios of the 5th and 95th percentile values for the aggregated distributions indicate that the width of the uncertainty distribution is typically greater for the aggregated distributions than for the individual elicited distributions.

4.4.3 Summary of Aggregated Wet Deposition Assessments

Figures 4.13 through 4.16 plot the central measure and the uncertainty measure of the aggregated distributions for aerosols and elemental iodine removed by rain. As with the dispersion and dry deposition results, the ratios of the 5th and 95th percentile values indicate that the widths of the aggregated distribution are typically greater than for the individual elicited distributions. The central measures for the aggregated wet deposition distributions appear consistent with the individual distributions.

4.5 Processing of Aggregated Distributions into Distributions on Code Input Parameters

This section reviews the results of activities directed toward the transformation of the dispersion and wet deposition aggregated elicited distributions into distributions over consequence code input parameters. The dry deposition elicitation questions queried the actual consequence code input parameters, and further processing of the aggregated dry deposition distributions was unnecessary. A more in-depth discussion of the application of and results achieved with the processing methodologies is presented in Volume III, Appendix E.

4.5.1 Development of Distributions Over Wet Deposition Code Input Parameters

Distributions for the wet deposition consequence code input parameters were developed from the aggregated elicited wet deposition distributions utilizing the PARFUM method discussed in Section 3.5.2 of this document. The elicited aggregated distributions were well replicated by processing the distributions developed over the wet deposition consequence code input parameters through the wet deposition models of the consequence codes. Representative processed wet deposition results are compared to aggregated elicited data in Figures 4.21 through 4.26. The data developed from the distributions over the code input parameters are designated as the PARFUM data in these plots.

4.5.2 Development of Distributions Over Dispersion Code Input Parameters

Two sets of distributions over the dispersion consequence code input parameters were independently developed utilizing the Sigma and Chi processing methodologies discussed in Section 3.5.2 of this document. The Sigma methodology developed distributions over the code input parameters from the equal weighted aggregated elicited distributions for χ_c/Q and s_y. The Chi methodology developed distributions over the input parameters from the equal weighted aggregated elicited distributions for χ_c/Q, χ_y/χ_c, and χ_z/χ_c. Figures 4.27 through 4.34 compare the aggregated elicited data to the data obtained by processing the Chi- and Sigma-developed code input parameter distributions through the MACCS and COSYMA GPM. Figures 4.27 through 4.30 compare χ_c/Q and σ_y values for the 3 km and 10 km downwind distances. The χ_c/Q and σ_y values developed from both the Chi and Sigma code input distributions show good agreement with the aggregated elicited distributions. The Sigma method generally more accurately replicates the aggregated elicited values, although the difference between the values obtained with the Sigma and Chi processing methodologies is not significant.

Figures 4.31 through 4.34 compare the χ_y/χ_c and the χ_z/χ_c values for the 0.5 km and 1 km downwind distances. Although most of the experts relied on the GPM for the development of the median values for their distributions, the 5th and 95th percentile values were developed using knowledge from other sources, typically experimental data. As a result, two of the eight dispersion experts provided 95th percentile values for χ_y/χ_c and χ_z/χ_c greater than one, which resulted in 95th percentile values greater than one in the aggregated distributions for χ_y/χ_c and χ_z/χ_c. The GPM cannot process χ_y/χ_c and χ_z/χ_c values greater than one. In order to fully utilize and replicate the elicited information in the Chi methodology (the Sigma methodology does not utilize elicited χ_y/χ_c and the χ_z/χ_c data), modification of the GPM (e.g., the development of a smooth Gaussian profile superimposed with fluctuations) would be necessary. The development of alternative dispersion models for the MACCS and COSYMA codes was not within the scope of this project. Distributions over code input parameters were therefore developed from that portion of the aggregated elicited distributions which were consistent with the GPM (The 100th percentile values for χ_y/χ_c and χ_z/χ_c were assigned a value of one, their maximum allowable value in the GPM). Because of the constraints of the GPM, the Chi methodology could not fully replicate the χ_y/χ_c and the χ_z/χ_c aggregated elicited data. The value χ_z/χ_c was the least well duplicated elicited variable. The Sigma method was not designed to replicate data relating to the fluctuations in the plume profile, χ_y/χ_c and χ_z/χ_c, although these values can be calculated from the dispersion code input parameters developed using the Sigma method. As would be expected, the Chi methodology more accurately replicates the 5th and 50th percentile χ_y/χ_c and χ_z/χ_c aggregated data.

The project staff decided to use the Sigma method for the development of the final distributions on consequence code input parameters. The Sigma method only represents uncertainty in crosswind plume growth and χ_c/Q. It does not attempt to model the uncertainty in the plume profile, and therefore does not process χ_y/χ_c and χ_z/χ_c elicited data. It was concluded that the uncertainty in plume profile cannot be captured without the modification of the GPM implemented in the consequence codes.

4.6 Comparison of Results from Current Study to Code Calculated Values and Past Uncertainty Studies

This section compares the dispersion results obtained by the present study to the parameter values calculated by MACCS and the dispersion and deposition data obtained from past uncertainty studies.

4.6.1 Comparison of Cross-Wind Dispersion Values Calculated by MACCS and Values Obtained from the Processed Aggregated Elicited Distributions

Tables 4.1 and 4.2 compare the 5th, 50th, and 95th percentile values for σ_y developed using the Sigma processing methodology with the values predicted by the MACCS and COSYMA power law models for dispersion case A-1 (very unstable meteorological conditions) and dispersion case A-4 (moderately stable meteorological conditions), respectively. The values predicted by MACCS and COSYMA are between the 5th and 50th percentile values predicted by the distributions developed from the elicited data. This data indicates that the σ_y values used in the past in the MACCS and COSYMA codes are not the best estimate (in terms of being the median value) for σ_y as predicted by the experts in this study.

4.6.2 Comparison of Current Results to Past Uncertainty Studies Performed in Europe

The equal weighted aggregated results from the current study, the equal weighted aggregated results from the pilot study, and the results obtained from an uncertainty analysis of the dispersion module of the COSYMA consequence code are compared in Figures 4.35 through 4.38. The uncertainty study was conducted by KfK.[1] The uncertainty study considered only the model parameter uncertainties. Meteorological and environmental conditions were thought to be well defined and thus not sources of uncertainty. In Figures 4.35 and 4.36 the medians and widths of the s_y uncertainty distributions are compared. In Figures 4.37 and 4.38 the medians and the widths of the distributions are compared for the centerline concentration ratios (χ_c/Q). The medians of all of the studies are comparable. The

Table 4.1 Values for σ_y for Case A-1 based on distributions over dispersion code input parameters and σ_y as defined in the MACCS and COSYMA codes

Downwind Distance (km)	σ_y (meters)				
	5%	50%	95%	Power Law (MACCS)	Power Law (COSYMA)
.5	48	160	740	100	133
1.0	92	300	1400	187	231
3.0	250	830	3800	505	554
10.0	730	2500	12000	1500	1445
30.0	1900	6800	33000	4000	3465

Table 4.2 Values for σ_y for case A-4 based on distributions over dispersion code input parameters and σ_y as defined in the MACCS and COSYMA codes

Downwind Distance (km)	σ_y (meters)				
	5%	50%	95%	Power Law (MACCS)	Power Law (COSYMA)
.5	13	48	150	20	33
1.0	23	88	270	37	57
3.0	57	230	730	100	138
10.0	150	640	2100	290	359
30.0	370	1600	5900	800	861

widths of the distributions from the two expert elicitation exercises are much greater than the widths of the distributions from the KfK uncertainty study, which were developed by consequence analysts.

Figures 4.39 and 4.40 compare the elemental iodine and aerosol (1 μm and 3 μm) dry deposition velocity on grass (similar to meadow) as developed in Fischer, Ehrhardt and Hasemann[2], the CEC pilot study as presented in Cooke[3], and the current study. The Fischer, Ehrhardt and Hasemann study developed dry deposition velocities to grass only for 1 μm aerosols. The distributions developed in the Fischer, Ehrhardt and Hasemann study were developed by consequence experts, not by panels of phenomenological experts in the appropriate fields. The pilot study distributions were obtained from panels of experts, but these experts were not trained in providing their judgments in terms of probability distributions. Also, in the pilot study the experts were all from the EC. In general the uncertainty attributed to the dry deposition velocity in the current study was much larger than the two past studies. Also the median values tended to be higher in the current study.

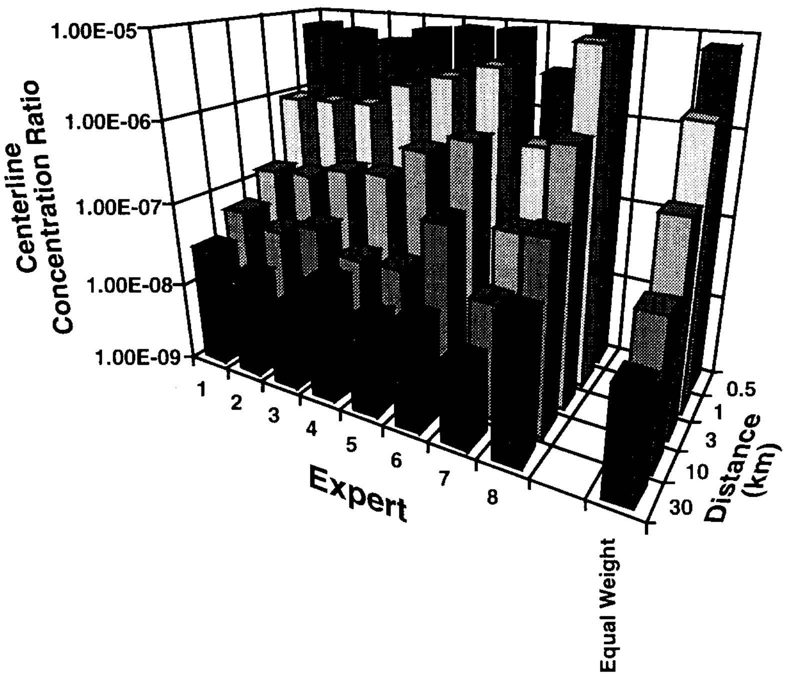


Figure 4.1 Elicited values for 50th percentile χ_c/Q, stability class A

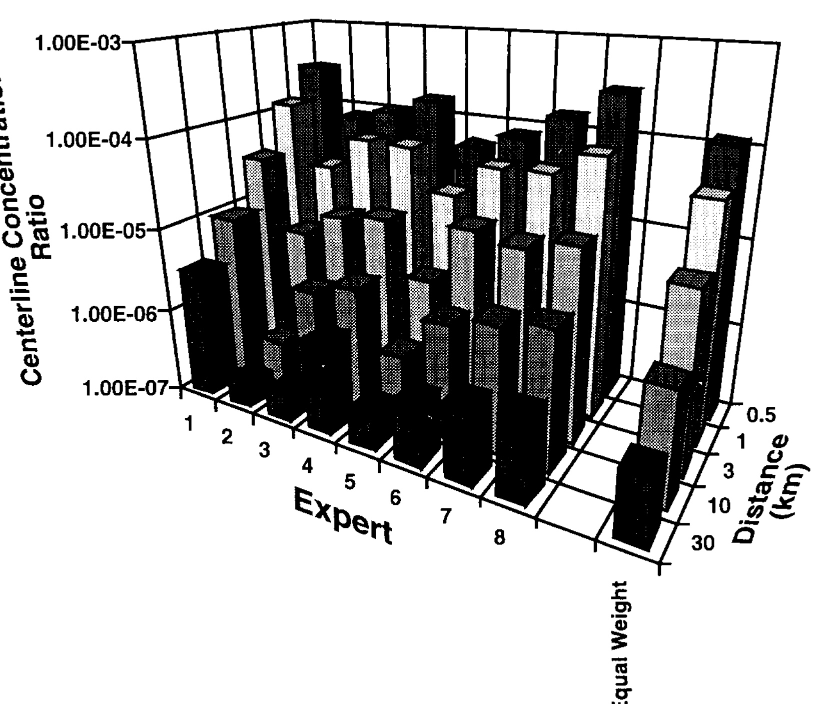


Figure 4.2 Elicited values for 50th percentile χ_c/Q, stability class E/F

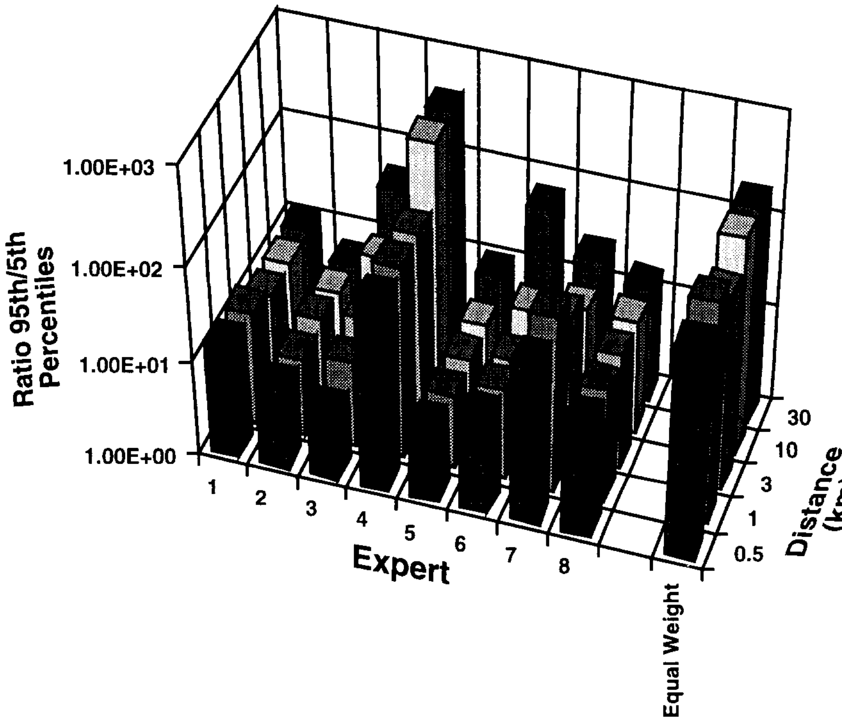


Figure 4.3 Ratio of 95th/5th percentile elicited χ_c/Q, stability class A

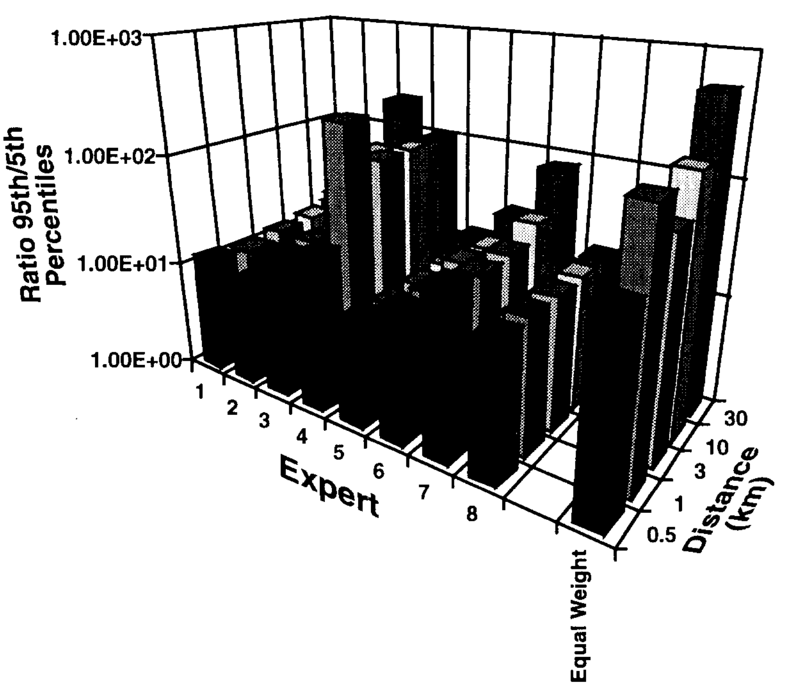


Figure 4.4 Ratio of 95th/5th percentile elicited χ_c/Q, stability class E/F

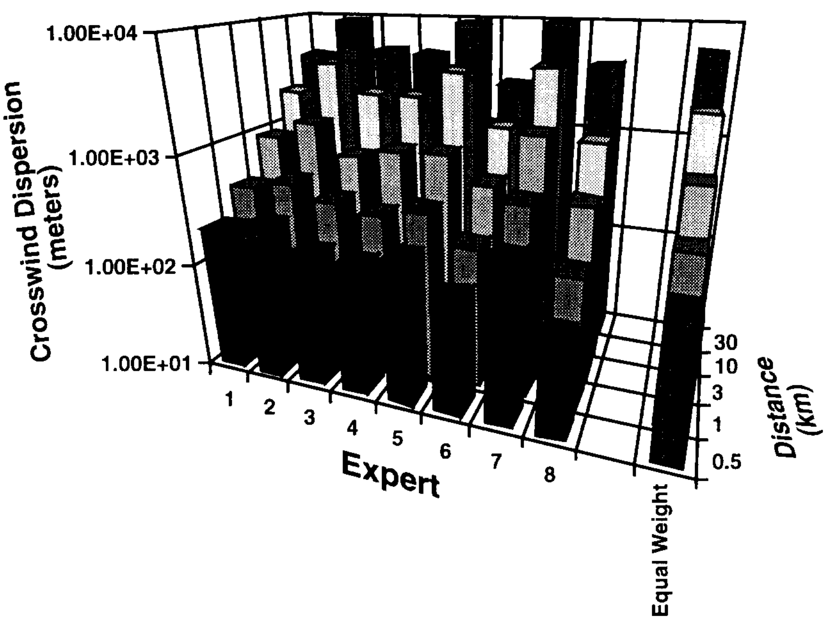


Figure 4.5 50th percentile elicited s_y (crosswind dispersion) values, stability class A

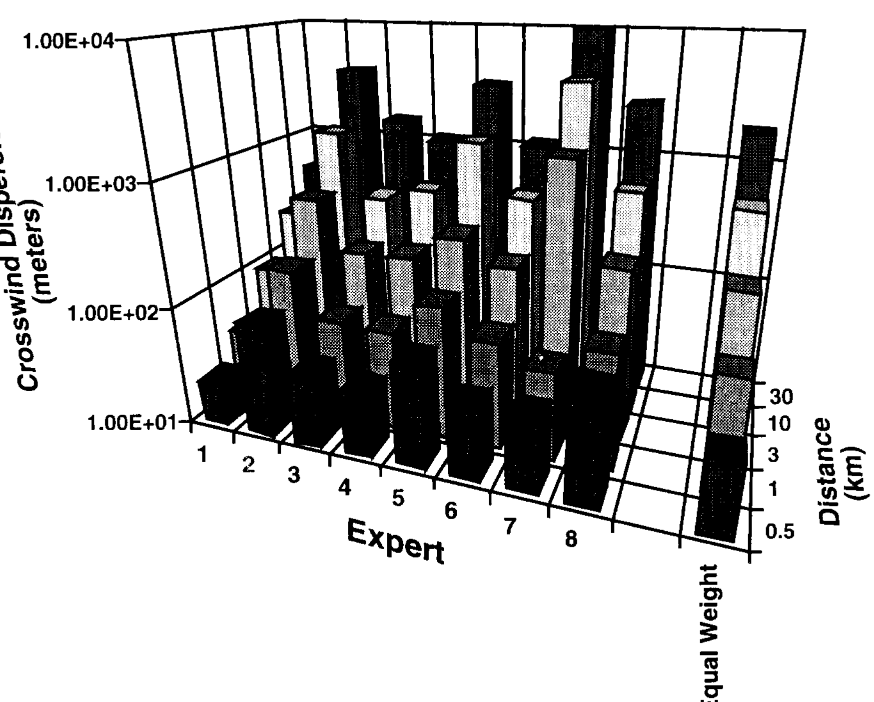


Figure 4.6 50th percentile elicited s_y (crosswind dispersion) values, stability class E/F

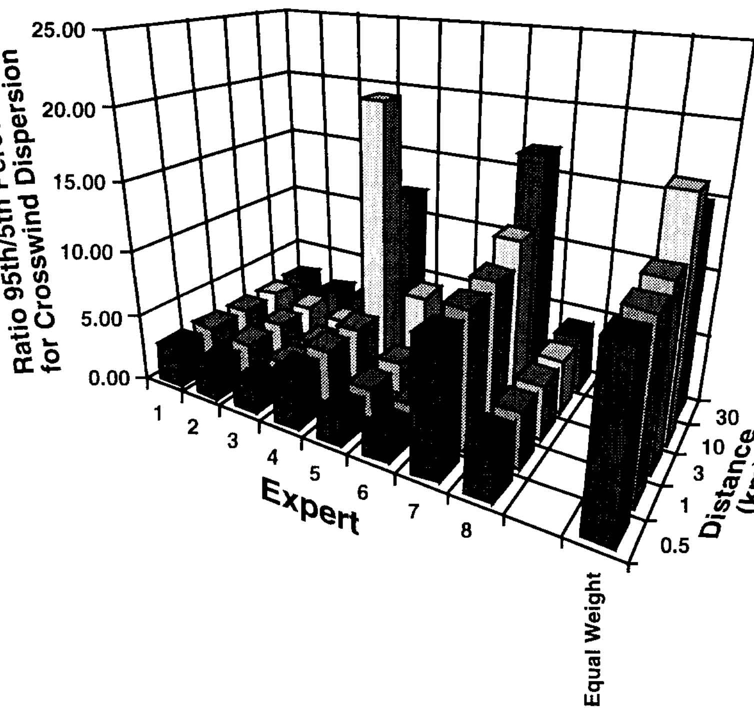


Figure 4.7 Ratio of elicited 95th/5th percentiles for the elicited s_y (crosswind dispersion), stability class A

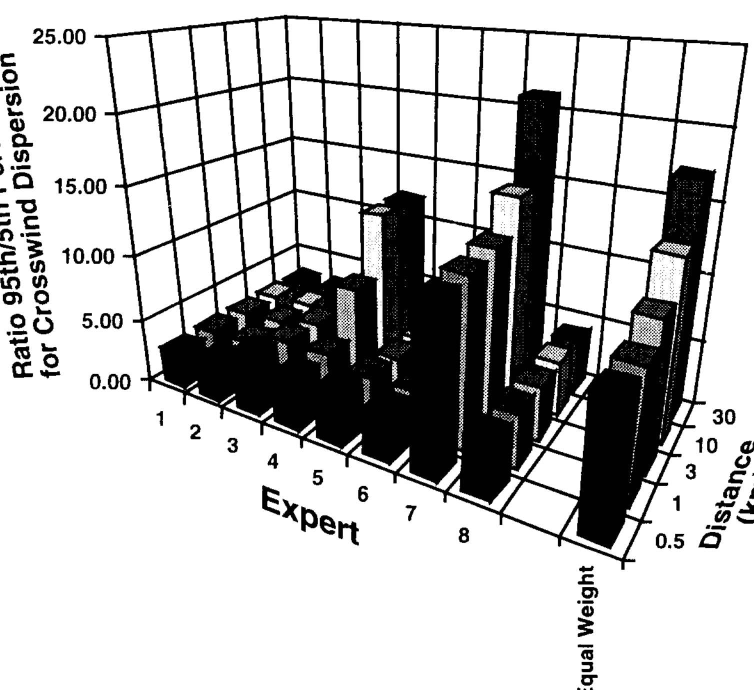


Figure 4.8 Ratio of elicited 95th/5th percentiles for the elicited s_y (crosswind dispersion), stability class E/F

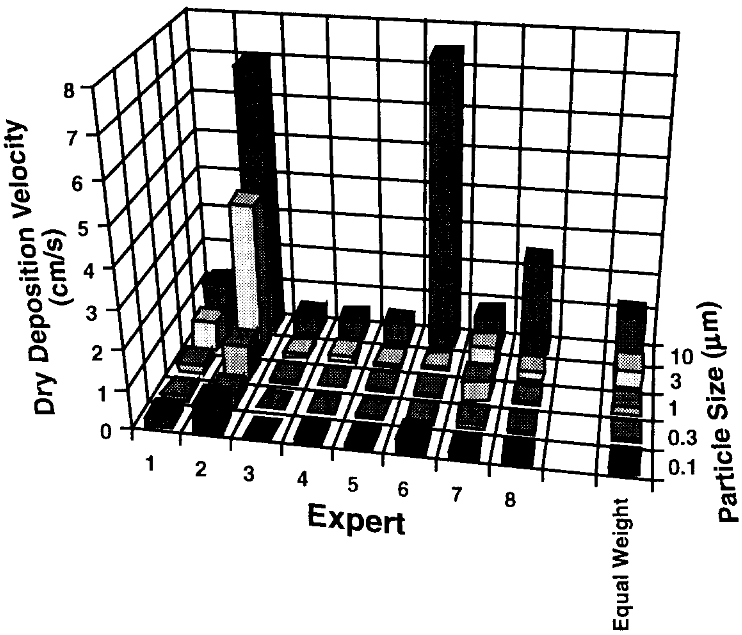


Figure 4.9 50th percentile elicited dry deposition velocity of aerosols onto urban surface, wind speed 2 /ms

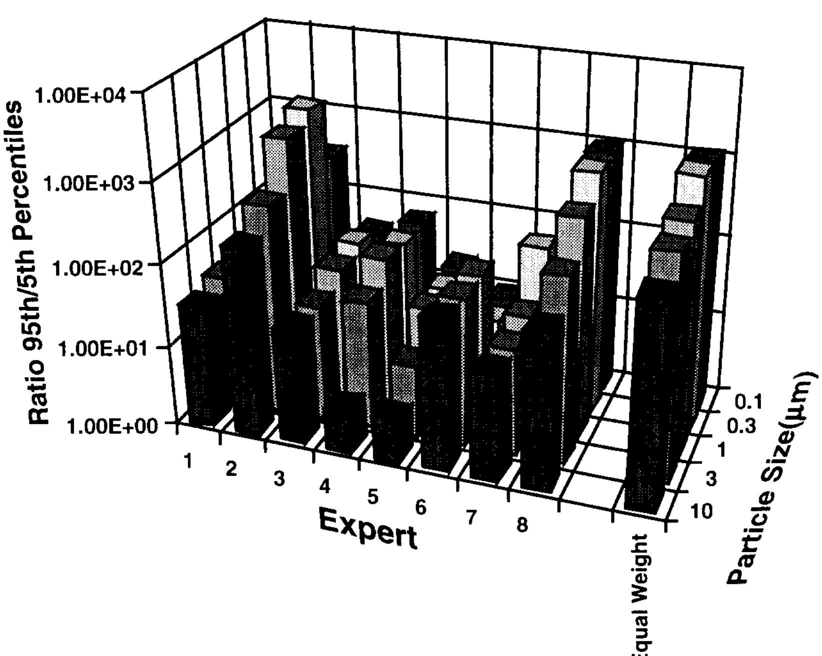


Figure 4.10 Ratio of 95th/5th percentile elicited aerosol dry deposition velocity, urban surface, wind speed 2 m/s

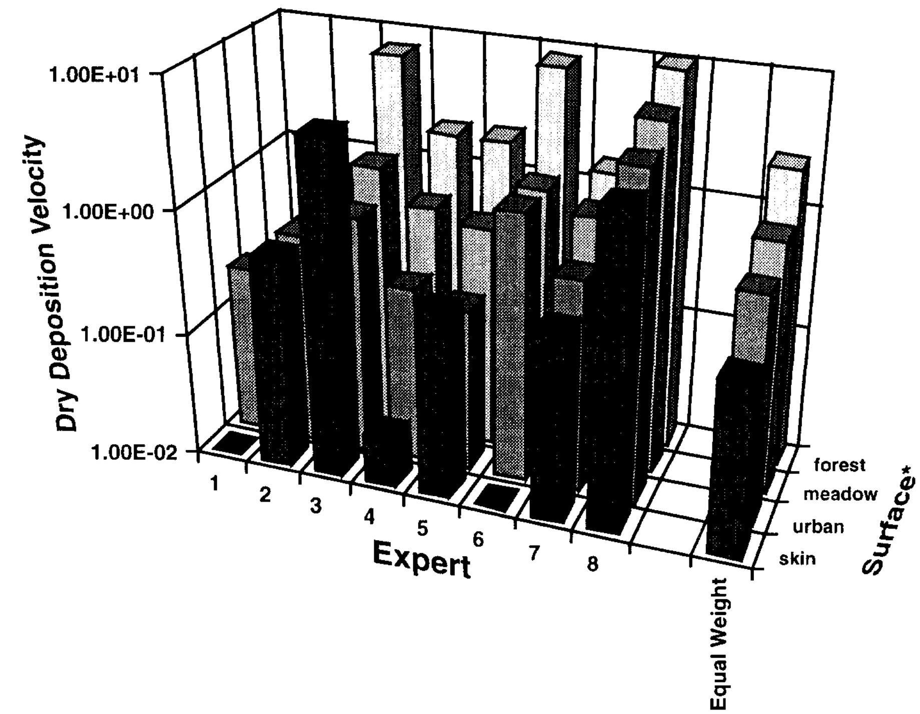


Figure 4.11 Elicited 50th percentile dry deposition velocities of elemental iodine, wind velocity 2 m/s

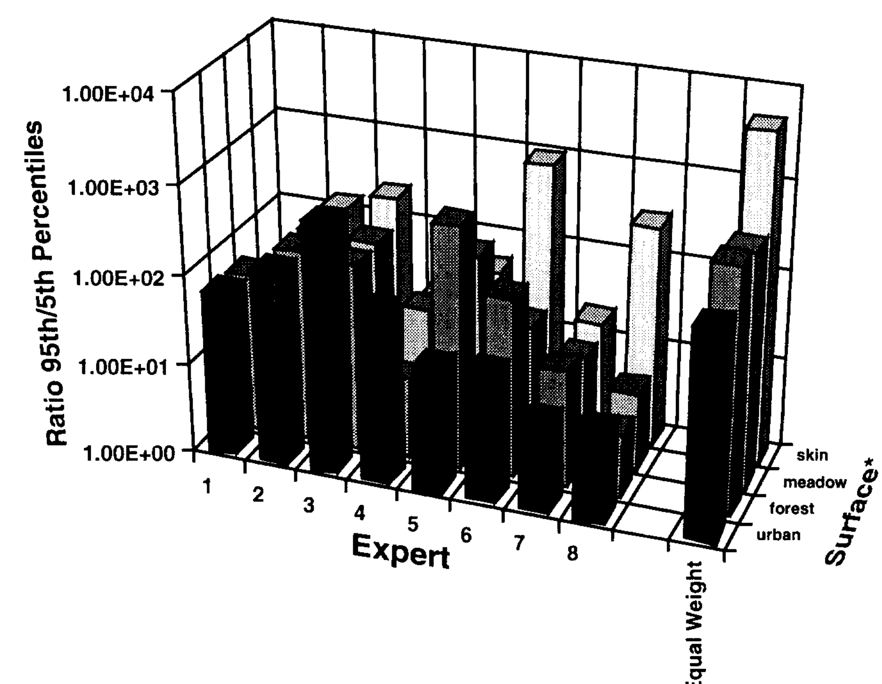


Figure 4.12 Ratio of 95th/5th elicited percentile values for the dry deposition elemental velocity of iodine, wind velocity 2 m/s

* The order of the surface parameters differs between Figures 4.11 and 4.12 so the data can be viewed more clearly.

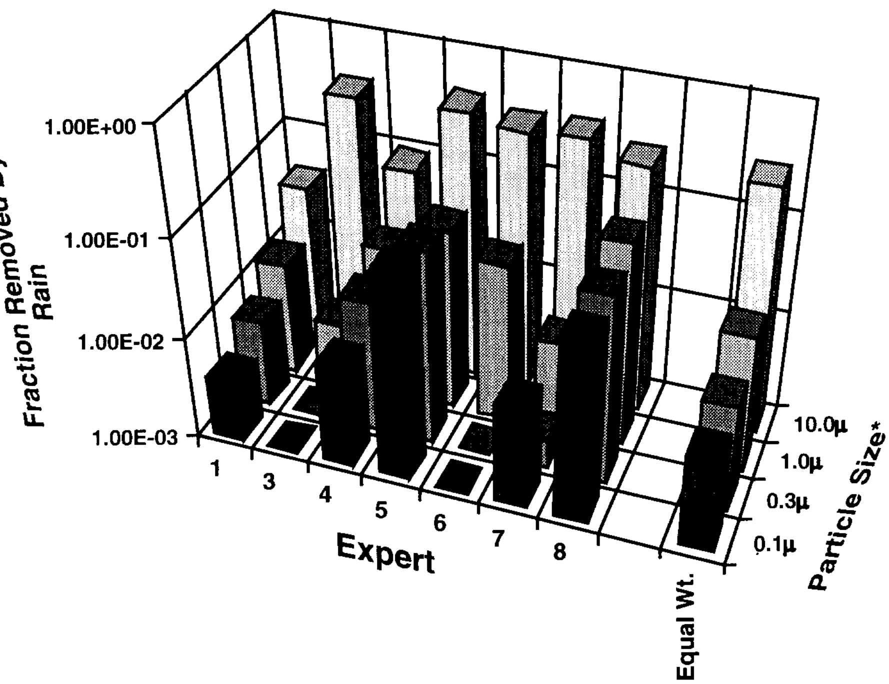


Figure 4.13 Elicited and aggregated (equal wt.) 50th percentile fraction of aerosols removed by rainfall of 0.33 mm during 10 minutes, wind velocity unspecified

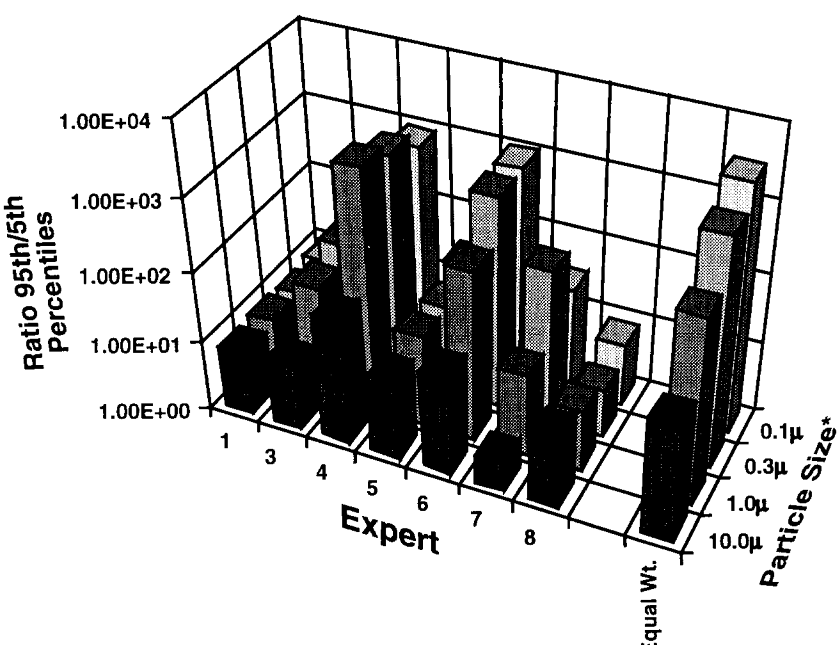


Figure 4.14 Ratio of 95th/5th elicited and aggregated (equal wt.) percentiles of fraction of aerosols removed by rainfall of 0.33 mm during 10 minutes, wind velocity unspecified

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* The order of the paricle size parameters differs between Figures 4.13 and 4.14 so the data can be viewed more clearly.

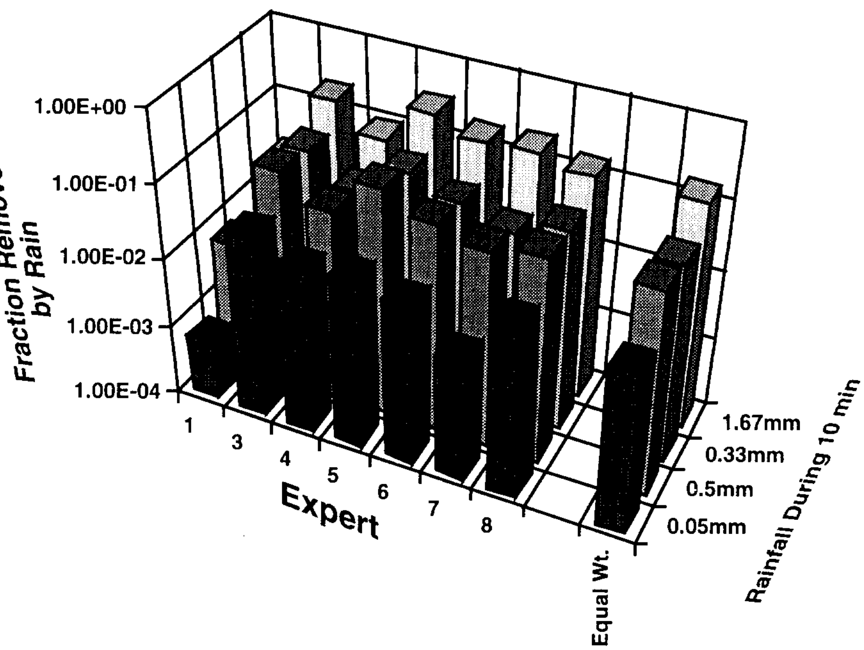

Figure 4.15 Elicited and aggregated (equal wt.) 50th percentile fraction of elemental iodine removed by rain during 10 minutes, wind velocity unspecified

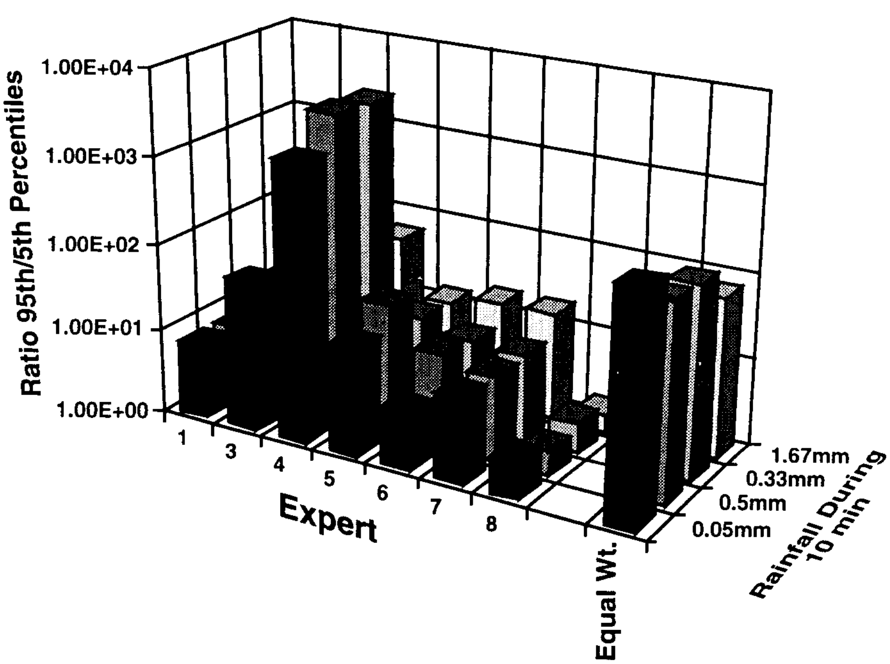

Figure 4.16 Ratio of elicited and aggregated (equal wt.) 95th/5th percentiles of fraction of elemental iodine removed by rain during 10 minutes, wind velocity unspecified

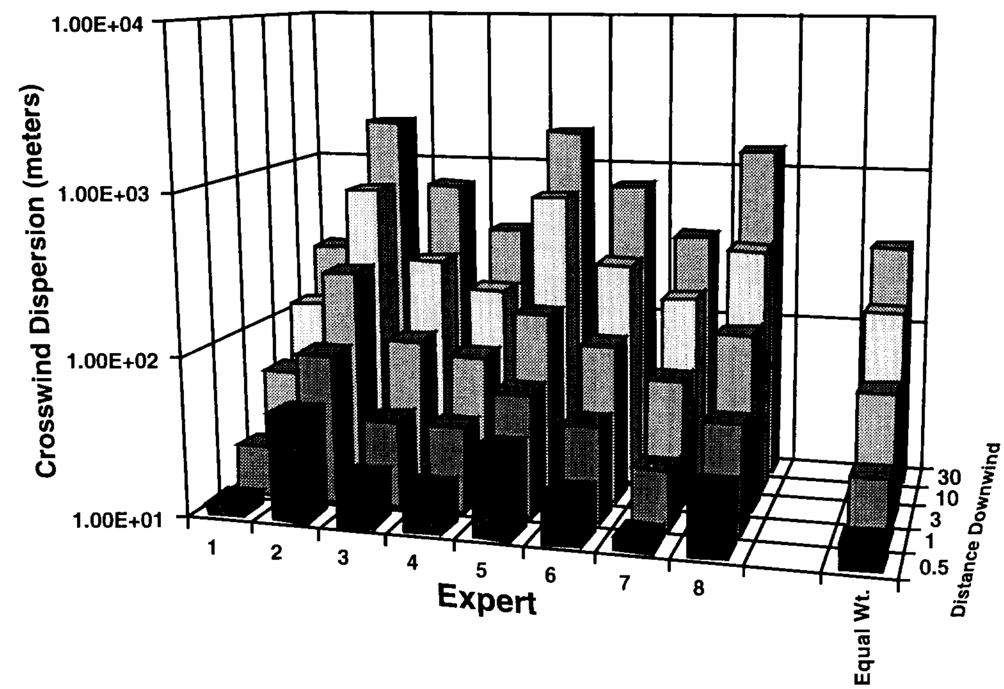

Figure 4.17 Elicited and aggregated 5th percentile data for s_y (crosswind dispersion), stability class E/F

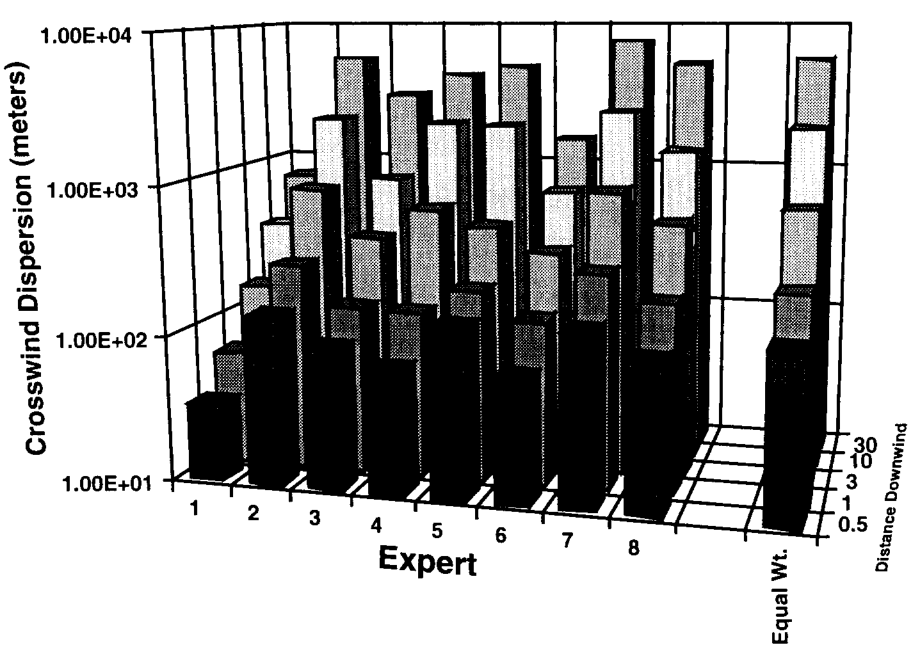

Figure 4.18 Elicited and aggregated 95th percentile data for s_y (crosswind dispersion), stability class E/F

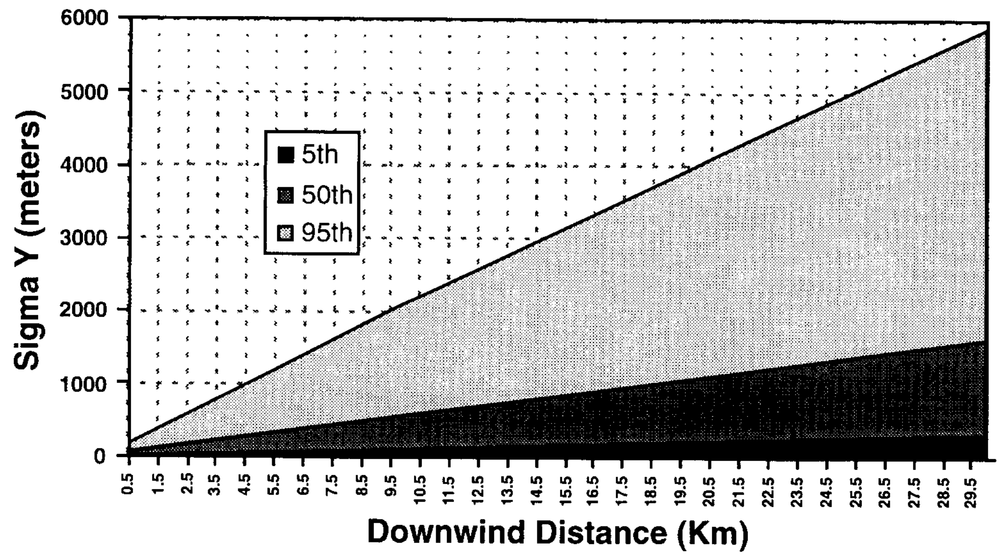

Figure 4.19 Uncertainty in plume growth, crosswind direction, stability class F (equal weighted aggregated elicited data)

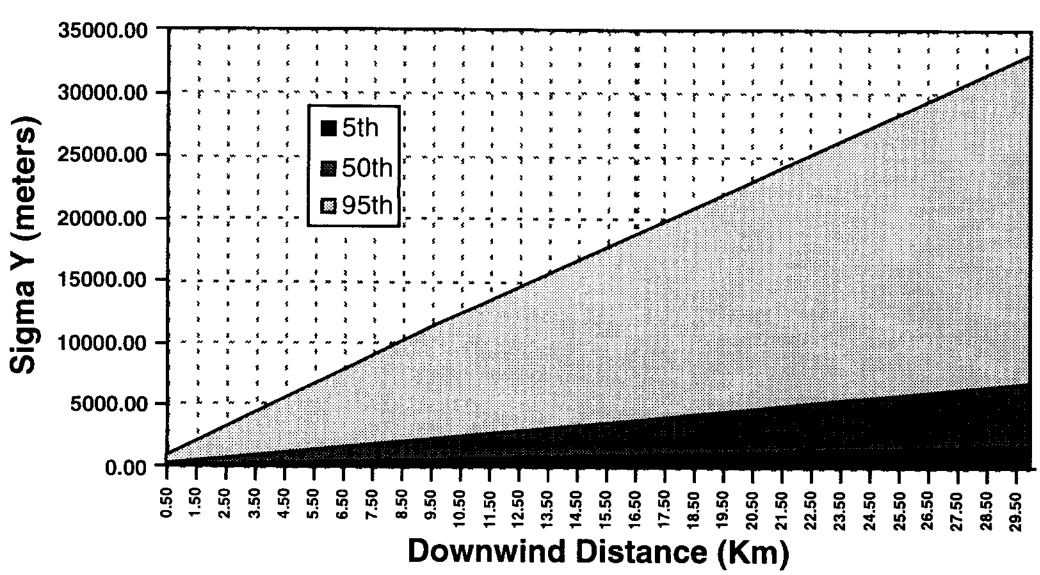

Figure 4.20 Uncertainty in plume growth, crosswind direction, stability class A (equal weighted aggregated elicited data)

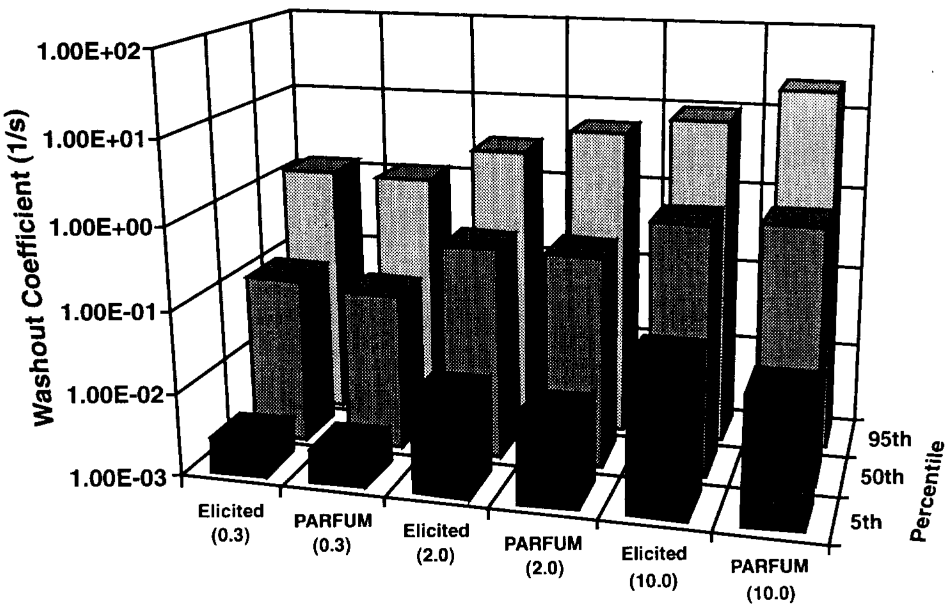

Figure 4.21 Elemental Iodine washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the ran intensity (mm/hr)

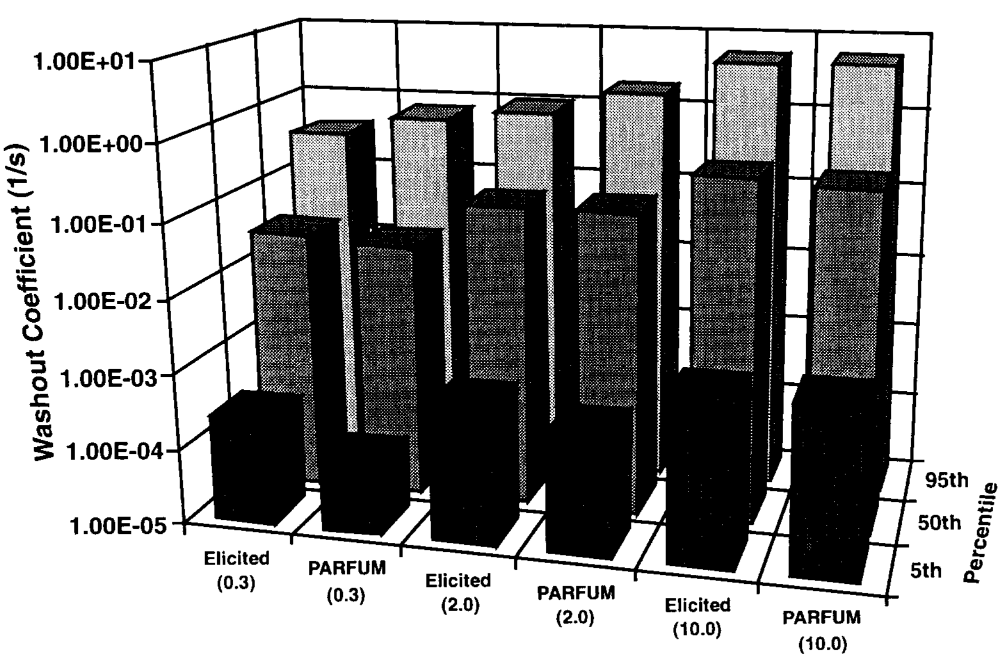

Figure 4.22 Methyl Iodine washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the rain intensity (mm/hr)

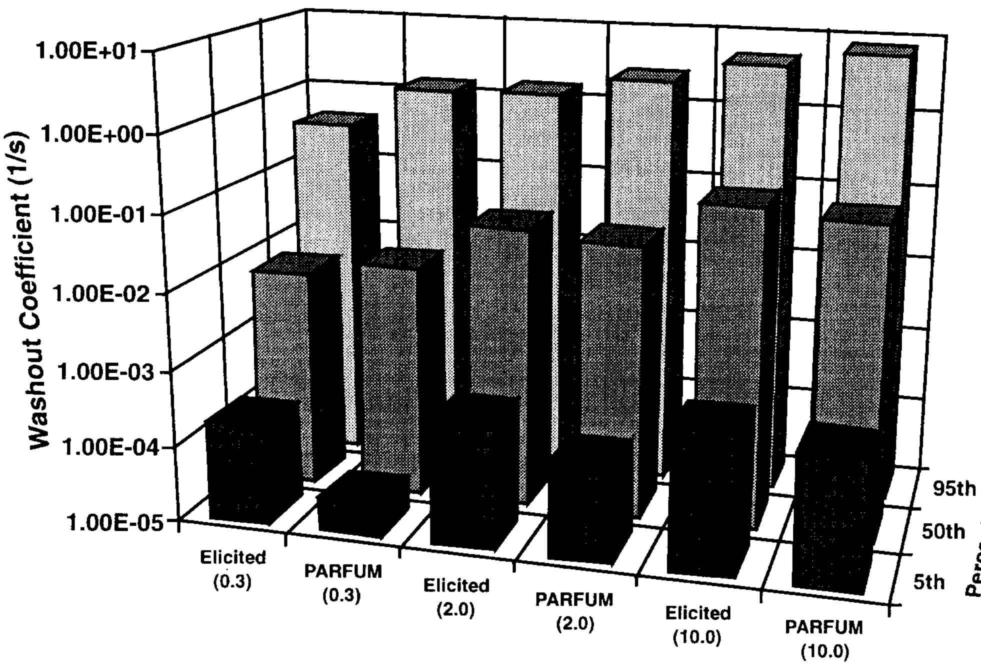

Figure 4.23 0.1 μ particle size aerosol washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the rain intensity (mm/hr)

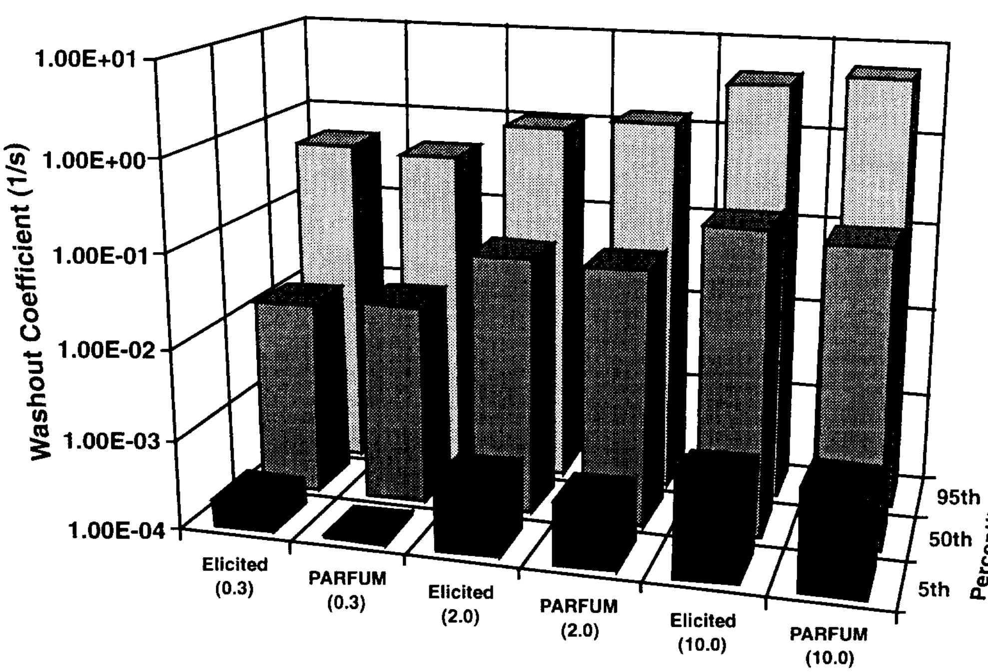

Figure 4.24 0.3 μ particle size aerosol washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the rain intensity (mm/hr)

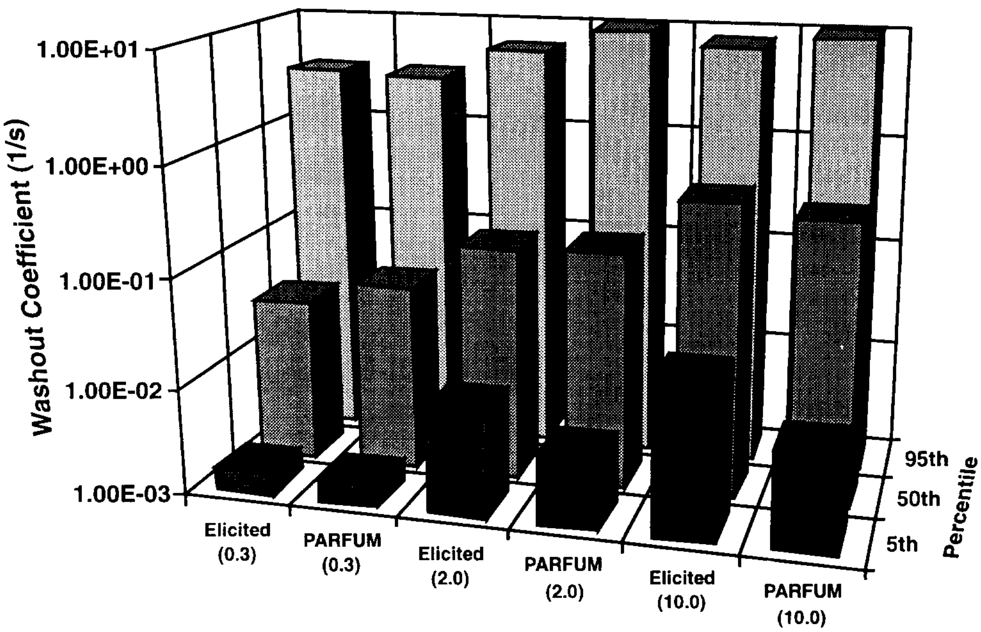

Figure 4.25 1.0 μ particle size aerosol washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the rain intensity (mm/hr)

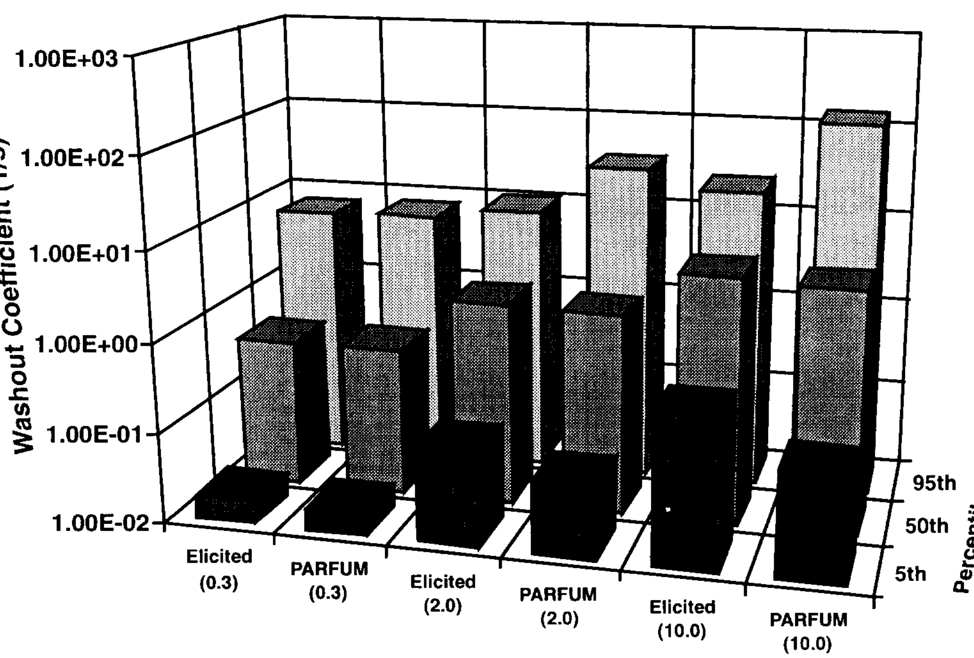

Figure 4.26 10 μ particle size aerosol washout data from aggregated elicited distributions (elicited) and calculated from distributions developed for code input parameters (PARFUM); numbers in parentheses along X-axis represent the rain intensity (mm/hr)

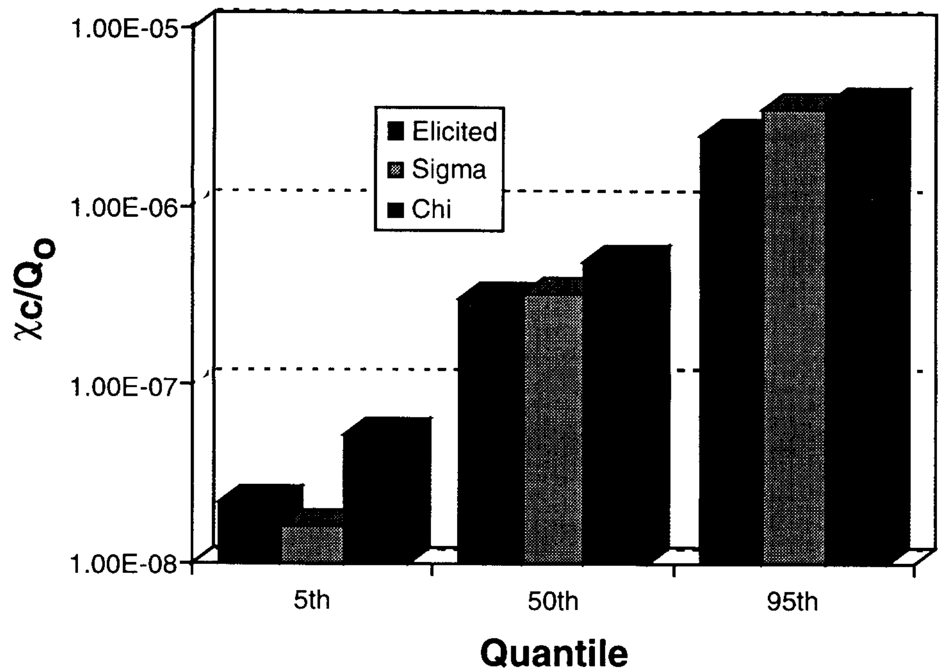

Figure 4.27 χ_c/Q, **stability class A, 3 km downwind distance**

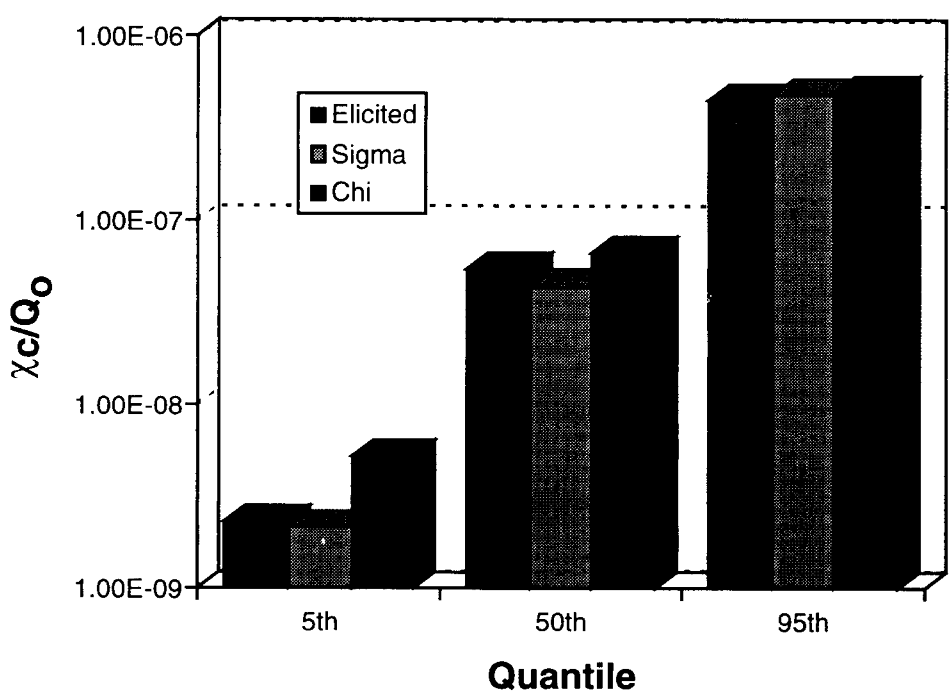

Figure 4.28 χ_c/Q, **stability class A, 10 km downwind distance**

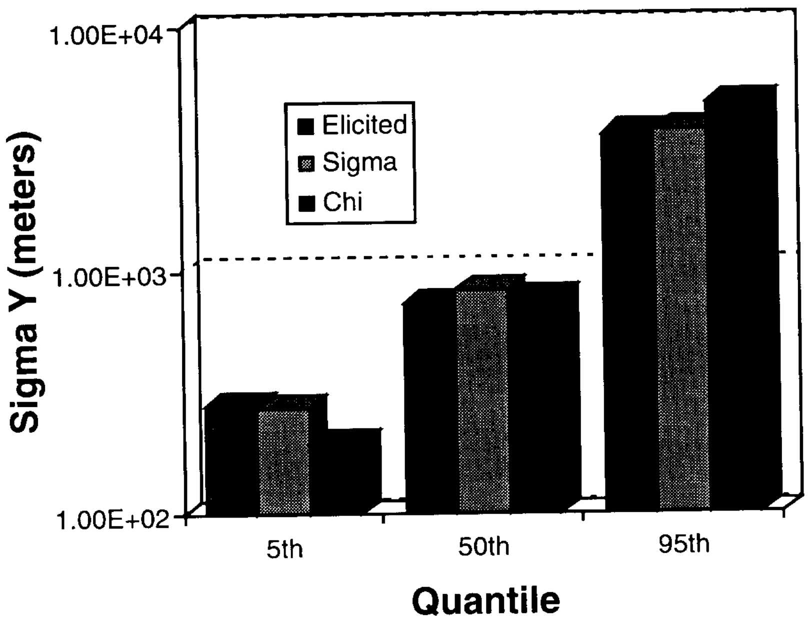

Figure 4.29 Sigma Y, stability class A, 3 km downwind distance

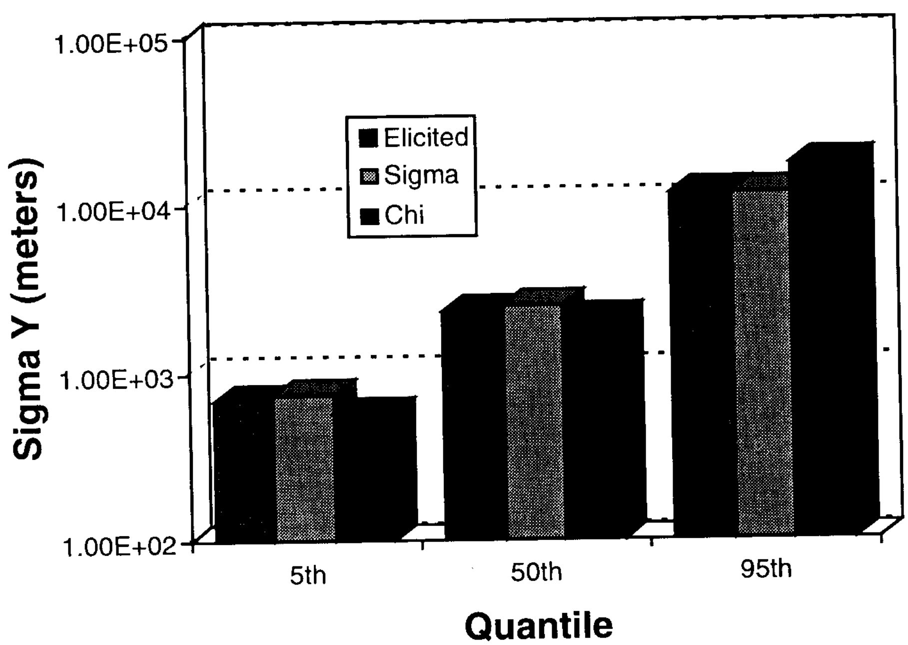

Figure 4.30 Sigma Y, stability class A, 10 km downwind distance

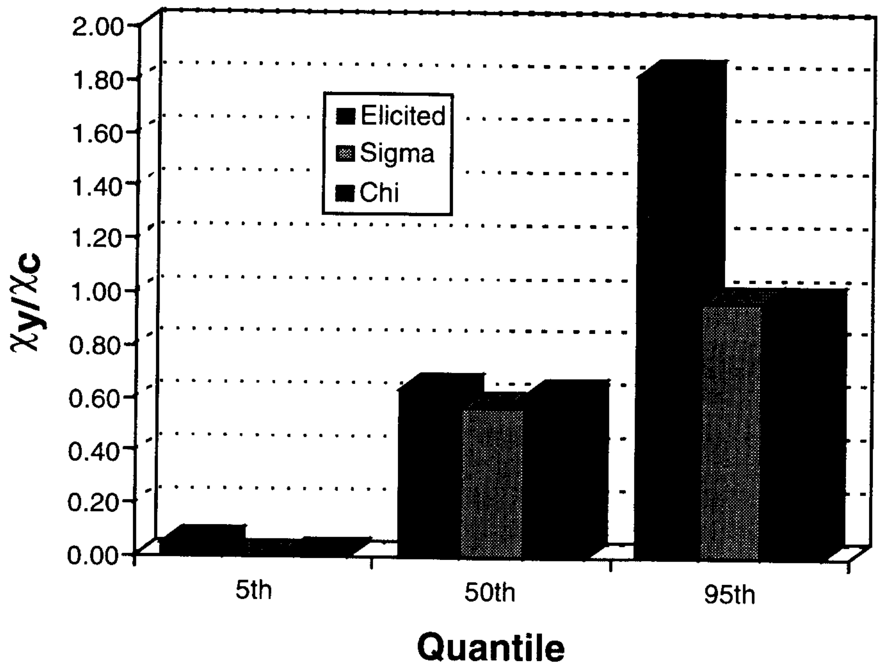

Figure 4.31 χ_y/χ_c, **stability class A, 500 m downwind distance**

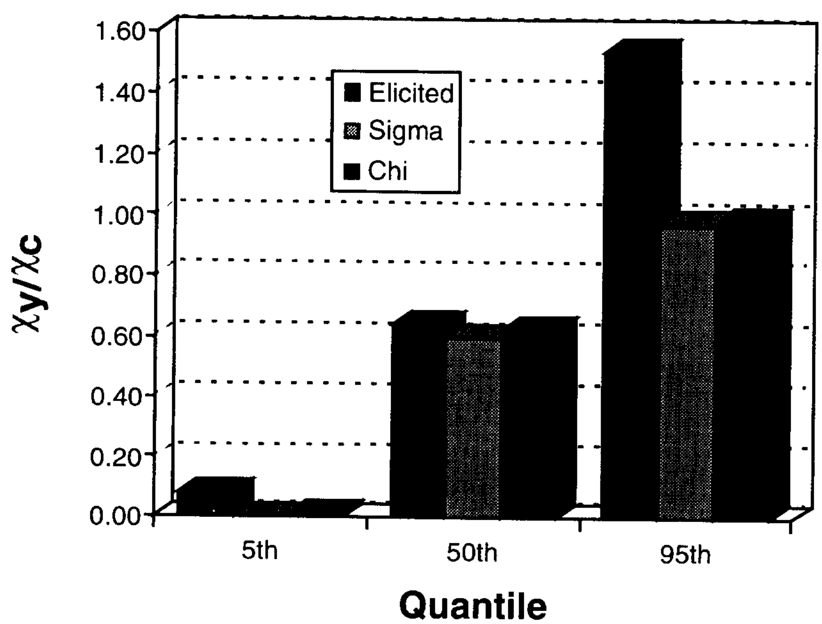

Figure 4.32 χ_y/χ_c, **stability class A, 1 km downwind distance**

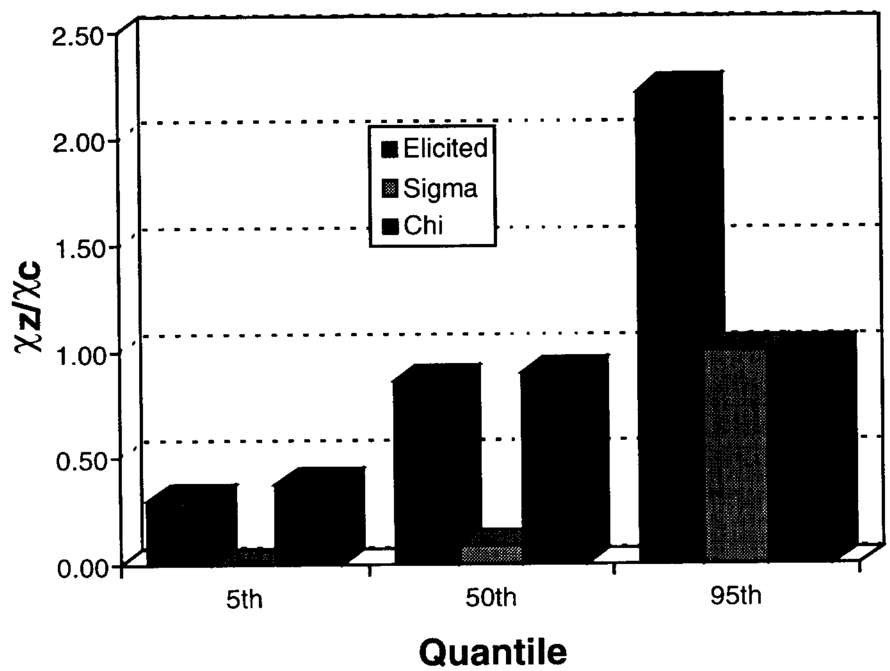

Figure 4.33 χ_z/χ_c, stability class A, 500 m downwind distance

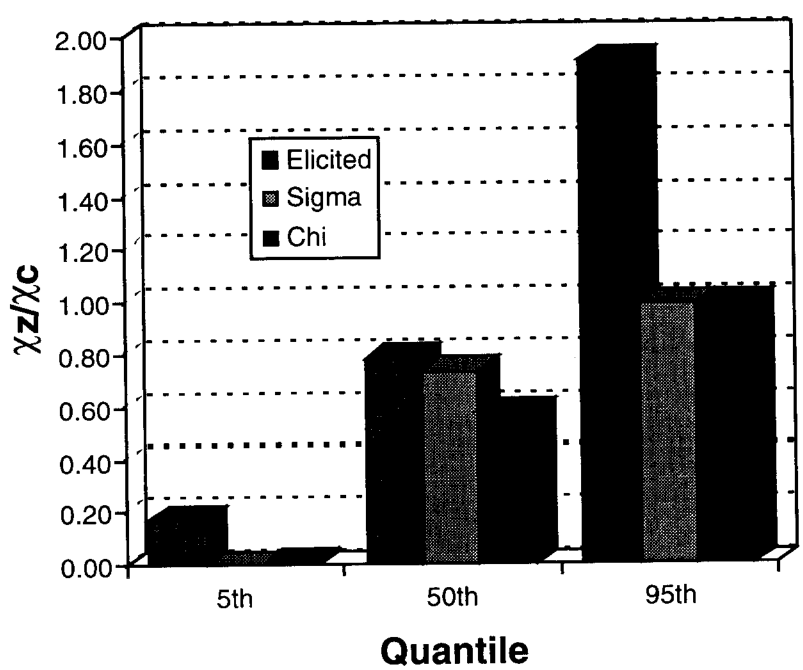

Figure 4.34 χ_z/χ_c, stability class A, 1 km downwind distance

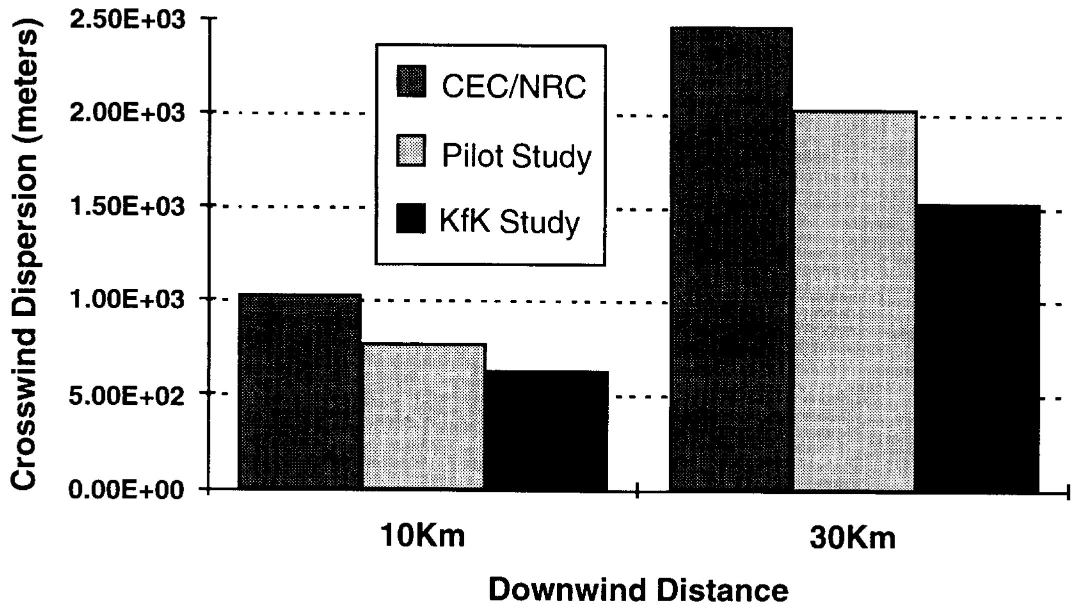

Figure 4.35 Comparison of aggregated 50th percentile (equal weighting) elicited s_y (crosswind dispersion) data for three studies, stability class D

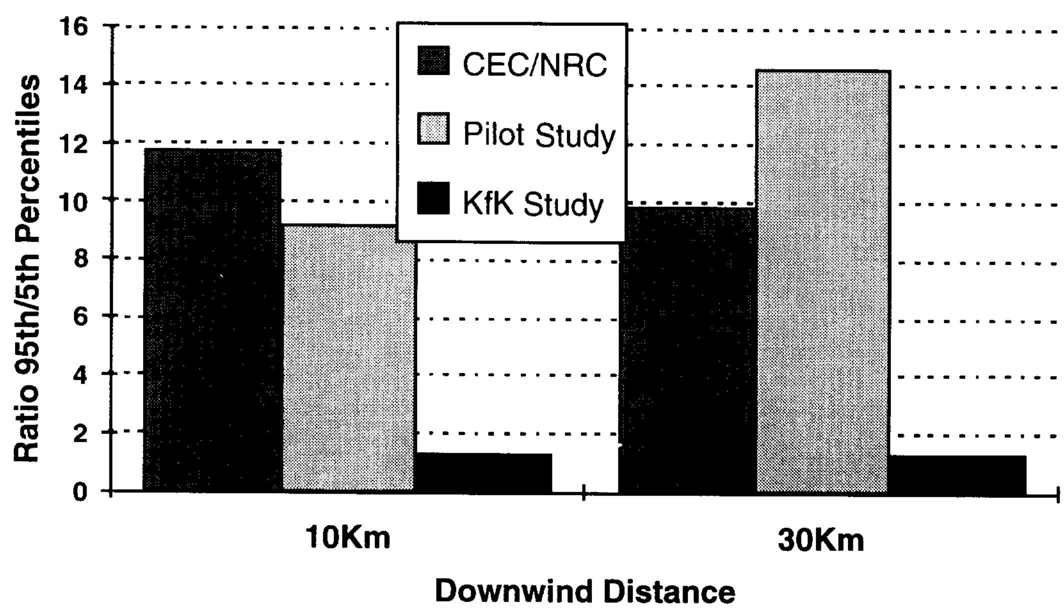

Figure 4.36 Ratio of 95th/5th percentile aggregated (equal weighting) values for elicited s_y (crosswind dispersion), stability class D

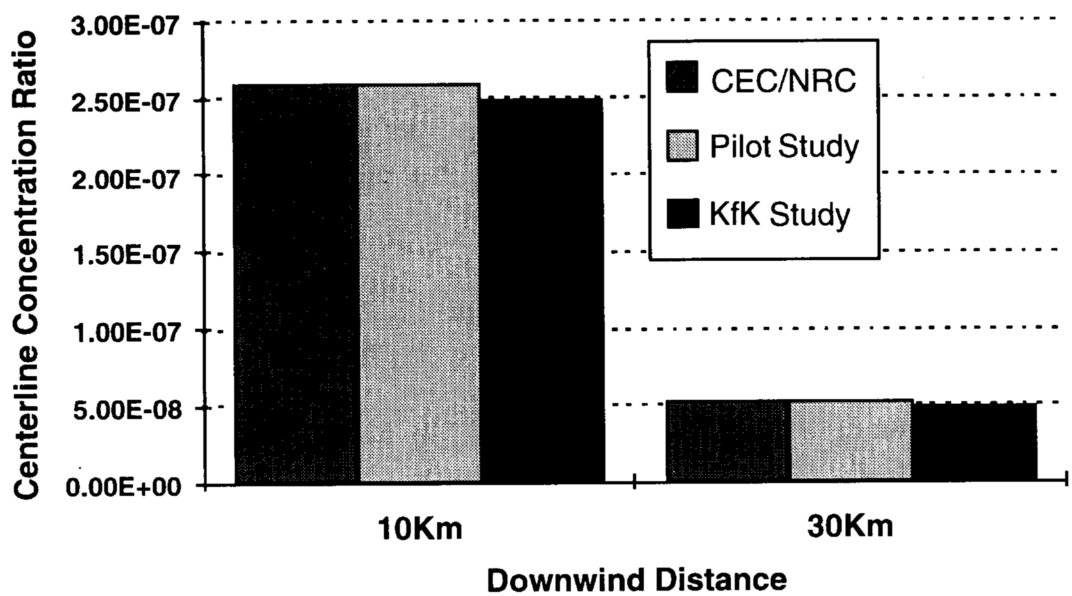

Figure 4.37 Aggregated 50th percentile values (equal weighting) for the elicited χ_c/Q, stability class D

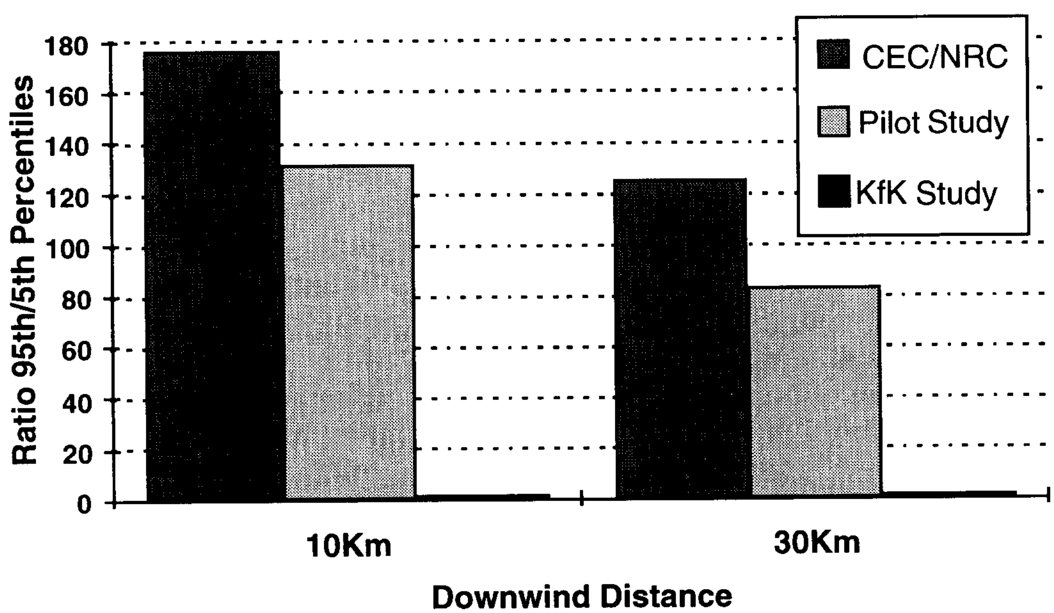

Figure 4.38 Ratio of 95th/5th percentile aggregated (equal weighting) values for the elicited χ_c/Q, stability class D

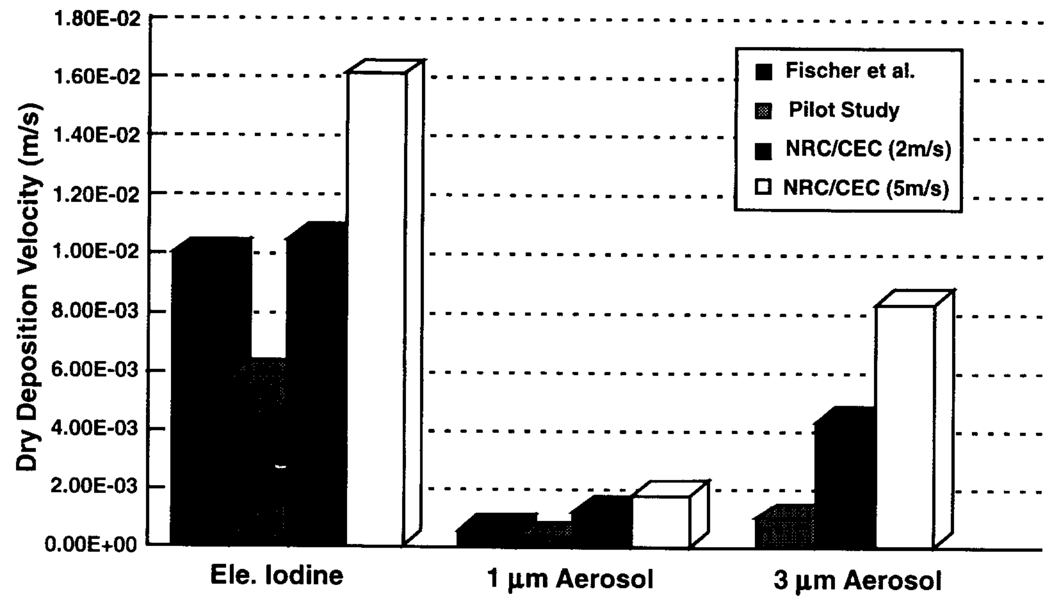

Figure 4.39 Comparison of 50th percentile dry deposition velocities from the NRC/CEC uncertainty study and past uncertainty studies; values in parentheses represent the wind speed assumed for the variable

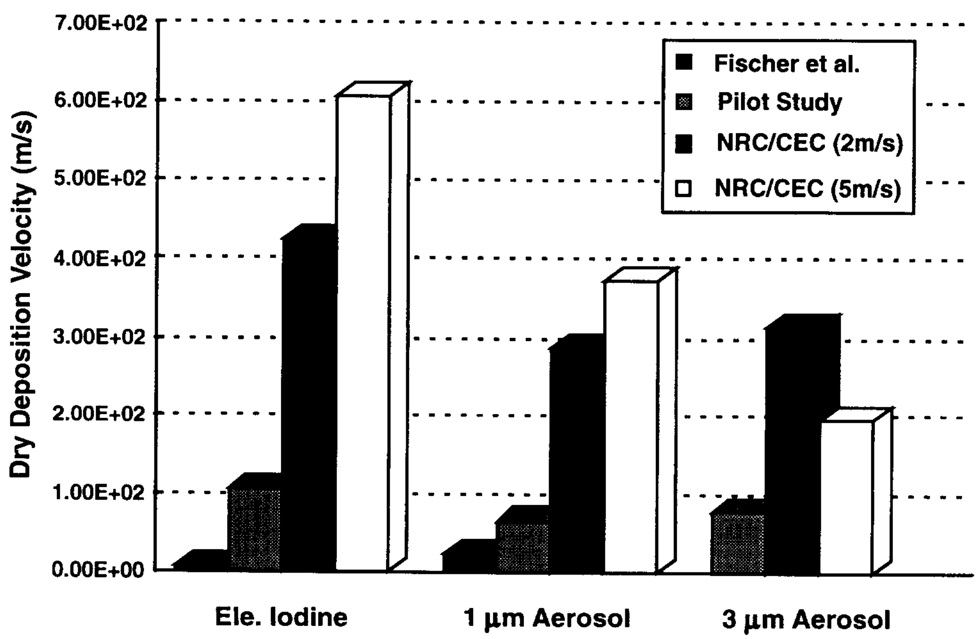

Figure 4.40 Comparison of ratios of 95th/5th percentile dry deposition velocities from the NRC/CEC uncertainty study and past uncertainty studies; values in parentheses represent the wind speed assumed for the variable

4.7 References

1. Fischer, F., J. Päsler-Sauer, and J. Raicevic, Kernforschungszentrum Karlsruhe GmbH, "Uncertainty Analyses for the Atmospheric Dispersion Submodule of UFOMOD with Emphasis on Parameter Correlations," KfK-4447, Karlsruhe, Germany, August 1989.

2. Fischer, F., J. Ehrhardt, and I. Hasemann, Kernforschungszentrum Karlsruhe GmbH, "Uncertainty and Sensitivity Analyses of the Complete Program System UFOMOD and of Selected Submodels," KfK-4627, Karlsruhe, Germany, September 1990.

3. Cooke, R., Delft University of Technology, "Expert Judgment Study on Atmospheric Dispersion and Deposition," Reports of the Faculty of Technical Mathematics and Informatics No. 91-81, Delft, The Netherlands, 1991.

5. Summary and Conclusions

5.1 Project Accomplishments

In this project, teams from the NRC and CEC were able to successfully work together to develop and implement a unified process for the development of uncertainty distributions on consequence code input parameters. Staff with diverse experience and expertise from different organizations allowed a creative and synergistic interplay of ideas that would not have been possible if the teams had worked in isolation. Potential deficiencies in processes and methodologies were identified and addressed in this joint study that might not have received sufficient attention in studies conducted independently. It is firmly believed that the final product of this study bears a more eminent credibility than either organization could have produced alone.

Distributions on measurable atmospheric dispersion and deposition parameters were successfully elicited from distinguished experts. Aggregated distributions, developed by combining the individual elicited distributions, are now available for measurable atmospheric dispersion and deposition parameters. The aggregated elicited uncertainty distributions represent state-of-the-art knowledge in the areas of atmospheric dispersion and deposition. Uncertainty distributions on atmospheric dispersion and deposition code input parameters are also now available for use in performing consequence uncertainty analyses using the MACCS and COSYMA codes. The distributions for the code input parameters are available on computer media and can be obtained from the project staff.

5.2 Uncertainty Included in Distributions

The distributions elicited from the experts concern physically measurable quantities, conditional on the case structures provided to the experts. The individual distributions contain uncertainty that includes the coarseness of the initial conditions of the case structure and natural atmospheric variability. The experts were not directed to use any particular modeling approach but were allowed to use whatever models, tools, and perspectives they considered appropriate for the problem. The elicited distributions obtained were subsequently developed by the experts from a variety of information sources. The aggregated elicited distributions, therefore, include variations that result from different modeling approaches and perspectives.

The aggregated elicited dry and wet deposition distributions capture the uncertainty over the dry deposition velocity of particles of different sizes over different surfaces and the fraction of different types of particles removed by rain. The aggregated elicited dispersion distributions capture the uncertainty at several downwind distances over: (1) the ratio of the plume centerline concentration and the source strength, (2) the standard deviation of the plume width in the cross-wind direction, and (3) the ratio of the off-centerline plume concentrations at specified locations in both the vertical and crosswind directions relative to the plume-centerline concentration. The aggregated elicited dispersion distributions represent the uncertainty in cross-wind plume growth and provide information about the uncertainty in the vertical and cross-wind plume profiles.

The uncertainty represented in the aggregated elicited wet deposition distributions was successfully captured in the distributions developed over the wet deposition consequence code input parameters. The distributions developed over the dispersion consequence code input parameters duplicate the uncertainties contained in the aggregated elicited distributions, which are consistent with the Gaussian plume model (GPM) implemented in MACCS and COSYMA. The uncertainties from non-Gaussianalities provided in a few assessments cannot be addressed within the Gaussian framework of MACCS and COSYMA and therefore were not included in the distributions over the dispersion code input parameters. The distributions over the dispersion code input parameters represent the uncertainty in cross-wind plume growth and in the ratio of the plume centerline concentration and the source strength for a Gaussian plume. Uncertainty relating to the plume profile is not included in the dispersion code input parameter distributions.

The mathematical processing of the aggregated elicited data introduces additional uncertainty into the distributions, which is accomplished by extrapolating from the points that were elicited to other points necessary for consequence calculations. Additionally, some uncertainty is introduced because of imperfect mathematical processing to obtain distributions over code input parameters (although this error has been shown to be small for the wet deposition, Sigma, and Chi/Q data).

Additional uncertainty will be introduced when the distributions are implemented in the consequence models (MACCS and COSYMA). MACCS and COSYMA combine models from many phenomenological areas. Combinations of these models may or may not provide an optimal simulation of reality. It exceeds the scope of this study to include the uncertainty relating to the correctness of the combination of models applied in the consequence codes (completeness uncertainty as defined by the USNRC PRA Working Group).

5.3 Uncertainty Assessment With Fixed Models

The results of this project provide an indication of some of the problems that may be encountered while attempting a consequence uncertainty study with fixed models. Given a fixed model, unless the code input parameters happen to be physical quantities that can be elicited directly (such as in the dry deposition case) an approach such as that adopted in this exercise may result in complicated mathematical treatments to generate code input variable distributions. If a case structure is designed to be independent of any particular analytical model, data may be elicited which are incompatible with the fixed models in the consequence codes. It is not apparent how to rationalize the distributions generated for the model parameters by using only information that is compatible to the fixed model. A carefully designed case structure is subsequently crucial to minimize the complexity that can develop when distributions are not elicited over code input parameters directly and when elicited data must be processed through fixed models.

5.4 Application of Distributions

The results of this project will allow the atmospheric dispersion and deposition component of consequence uncertainty analyses to be performed in a manner consistent with the NUREG-1150 methodology. The risk integration step in the NUREG-1150 methodology (the step in which the uncertainty in all modules of the analyses was assessed) relied on Latin Hypercube Sampling (LHS) techniques. The dispersion and deposition distributions are available in a form compatible with LHS and other sampling techniques. The distributions obtained will allow the uncertainty analyst to perform consequence uncertainty studies that include uncertainties caused by atmospheric dispersion and deposition and, for internal event analyses, couple uncertainty information in an integrated PRA.

The methods of this project were also consistent with the NUREG-1150 philosophy in that an attempt was made to include all modeling perspectives, and consensus among the experts was not required. Although this project focused on the development of distributions for MACCS and COSYMA input parameters, the elicited information is non-model-specific and subsequently can be fitted by many other analytical models. In addition, the development of distributions over physically measurable parameters means that the distributions will have applications beyond the scope of consequence code uncertainty analysis (e.g., emergency response planning). The library of atmospheric dispersion and deposition uncertainty distributions will have many applications outside of the scope of this project.

The distributions also provide additional insights regarding areas where current consequence codes are deficient, and they subsequently can be a useful guide for directing future research.

5.5 Conclusions

Valuable information has been obtained from this exercise, despite the omission of uncertainties resulting from the non-Gaussian behavior of plumes. Uncertainty over cross-wind plume growth was encoded in distributions over the consequence code input parameters. Aggregated elicited distributions containing uncertainties over the plume profile are also now available. Encoding the plume-profile uncertainty into the distributions over the code input parameters would require the implementation of a modified GPM in the consequence codes. However, because the aggregated elicited information is non-model-specific, it can also be fitted by other non-Gaussian analytical models. The goal to create a library of atmospheric dispersion and deposition uncertainty distributions was fulfilled.

Furthermore, in this exercise, formal expert judgment elicitation has proven to be a valuable vehicle to synthesize the best available information by a highly qualified group. With a thoughtfully designed elicitation approach, addressing issues such as elicitation variable selection, case structure development, probability training, communication between the experts and project staff, and documentation of the results and rationale—followed by an appropriate application of the elicited information—expert judgment elicitation can play an important role. Indeed, it possibly will become the only alternative technique to assemble the required information when it is impractical to perform experiments or when the available experimental results do not lead to an unambiguous and a non-controversial conclusion.

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The development of two new probabilistic accident consequence codes, MACCS and COSYMA, was completed in 1990. These codes estimate the consequences from the accidental releases of radiological material from hypothesized accidents at nuclear installations. In 1991, the U.S. Nuclear Regulatory Commission and the Commission of the European Communities began co-sponsoring a joint uncertainty analysis of the two codes. The ultimate objective of this joint effort was to systematically develop credible and traceable uncertainty distributions for the respective code input variables. Because of the magnitude and expense required to complete a full-scale consequence uncertainty analysis, a trial study was performed to evaluate the feasibility of such a joint study by initially limiting efforts to the dispersion and deposition code input variables. A formal expert judgment elicitation and evaluation process was identified as the best technology available for developing a library of uncertainty distributions for these consequence parameters. This report focuses on the methods used in and results of this trial study.

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